Sustainable Agriculture and Food Security

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Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa

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Sustainable Agriculture and Food Security

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Foreword

Modern agricultural practices are dependent on fossil fuel-based external inputs with high carbon footprints that lead to severe environmental degradation and rapid depletion of natural assets. The food system has also become increasingly globalized and trade-dependent, which has led to increasing rates of forest clearance for agricultural use. The negative impacts of excessive use of chemical inputs such as fertilizers and pesticides on biodiversity and other ecosystem services are often ignored. According to the estimates of the international agencies, agricultural land-use changes alone are responsible, globally, for over 60% of the terrestrial biodiversity loss, 24% of greenhouse gas emissions, and 33% of soil degradation. Over the years, numerous high-impact publications and policy documents have emphasized the importance of adopting agroforestry and other sustainable land-use systems as an approach to meeting the demands of a growing population under increasing land constraints and climate change.

The scientific development of agroforestry technologies at various levels ranging from farmers' fields to landscapes has gained significant importance globally among different stakeholders. The major role that agroforestry could play in addressing several developmental and conservation issues such as degraded land rehabilitation, biodiversity conservation, food and nutritional security, and climate change mitigation has now been widely recognized. It is quite appropriate in this context that this book *Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa*, with chapters contributed by various experts, and edited by highly experienced agroforestry professionals Drs JC Dagar, SR Gupta, and GW Sileshi, is being published by Springer.

The chapters in the book explore a wide spectrum of agroforestry systems and practices ranging from the complex multistory homegardens to less intensive systems such as scattered trees on farmlands. The topics presented discuss emerging aspects of climate change, biodiversity conservation, restoration of degraded lands, and research-policy interface, covering a wide array of agroforestry practices across diverse agroecological and geographic locations of Africa and Asia. This is a vast region that is experiencing large-scale biodiversity loss and environmental degradation due to the rapid conversion of forests to cropland, human settlements, and industrial developments, resulting in frequent wildlife-human conflicts. The book presents summary accounts of the progress of agroforestry towards sustainable intensification of agriculture in the face of the highly adverse impacts of climate change during the past few decades. The role that agroforestry can play in restoring degraded landscapes and combating desertification is convincingly demonstrated by analyzing and synthesizing the field experiences. Overall, the book presents a synthesis of studies on agroforestry approaches to sustainable intensification of agriculture, by renowned experts in fields relevant to sustainable land management.

I am confident that this publication will be a useful reference book for students, researchers, entrepreneurs, conservation and development professionals, and others engaged in agroforestry research and sustainable development. I consider it an honor to write these few words of appreciation and congratulate the book's editors and chapter authors on this important, timely, and well-needed contribution.

University of Florida, Gainesville, FL, USA
P. K. R. Nair
April 2022

Preface

Asian and African countries are faced with various challenges including land degradation, biodiversity loss, and climate change and associated disasters such as frequent cyclones, Tsunamis, droughts, floods, and Covid-19 epidemics. Agroforestry can play a key role in mitigating the impacts of such disasters and allow recovery. It has also been shown to support agroecological transition to sustainable intensification, climate change mitigation and adaptation, ecosystem restoration, and biodiversity conservation. To increase productivity on existing agricultural lands with positive environmental and societal impacts, the time has come to take stock of past research and development in agroforestry and to explore the emerging trends to address emerging challenges in Asia and Africa for sustainable intensification, diversification, and sustainability.

During the past four decades, agroforestry has come of age and begun to attract the attention of the international scientific community, primarily as a means for sustaining agricultural productivity in marginal lands and solving second-generation problems such as salinization due to waterlogging and contamination of water resources due to use of excess nitrogen fertilizers and pesticides. There is a growing body of evidence showing that planting fertilizer trees can address decline in soil nutrients and organic matter. National governments across the Sahel are taking steps to control desertification and mitigate its effects through the Great Green Wall project and farmer-managed natural regeneration in Sub-Saharan Africa. Research efforts have shown that most of the degraded lands including ravine-engrossed, saline, waterlogged, and perturbed ecologies like mine spoils, and degraded coastal and mangrove areas can be made productive by adopting suitable modern agroforestry techniques. Substantial evidence also shows that farmers' income can be increased manyfold through highly remunerative agroforestry practices integrating plantation species, high-value medicinal and aromatic plants, indigenous fruit trees with value addition, livestock, poultry, fish, vegetables, and floriculture. New concepts such as tree-based climate-smart agriculture, fertilizer tree systems, multi-enterprise farming such as aquaculture keeping mangroves intact, and urban and peri-urban agroforestry have also gained increasing currency. The knowledge base of agroforestry is expending through systematic reviews and meta-analysis of the available data, with a rapid pace as illustrated by the increasing number and quality of agroforestry publications in different fields.

It is both a challenge and an opportunity to the scientific community working in this interdisciplinary field of agroforestry. To develop the strategies for moving forward, it is essential to evaluate the past and present status of research and concepts and think of the ways of moving ahead. To prepare themselves better for future challenges in the rapidly changing environment and to seize opportunities to solve the livelihood and nutritional problems of ever-increasing populations, scientists and policy makers need to have access to easily digestible information. Keeping in view of these concerns, contributions from eminent researchers and scholars with keen interest in agroforestry were solicited for this publication. The contributions represent original research, reviews, and syntheses that deal with the various aspects of agroforestry systems in Asia and Africa. The important aspects include adoption of agroforestry as an approach for sustainable intensification that can promote the climate change mitigation and adaptation agenda across Asia and Africa; the practical strategies for transforming drylands into productive, sustainable ecosystems through Farmer-Managed Natural Regeneration; the scope for integrating agroforestry in urban and peri-urban areas; resilience of agroforestry for restoring degraded landscapes for increasing crop yields, and improving ecosystem services; expanding dryland agroforestry on large scales such as the Great Green Wall initiatives to mitigate desertification; the role of silvopastoral systems in rehabilitating degraded lands for improving soil quality, and carbon sequestration for offsetting greenhouse gases; the agroforestry interventions for increasing food production from salt-affected marginal and waterlogged degraded landscapes; the agroforestry systems for enhancing food security and environmental security for resource-poor farmers; biodiversity and ecosystem services; agroforestry to improve plant, animal, and microbial diversity; how agroforestry improves biodiversity and reduces human and wildlife conflict; domestication and management of indigenous fruit trees in Africa; management and conservation of plant diversity in ethnic homestead gardens in the tropical regions of Asia and Africa; biodiversity conservation, livelihood security, and carbon sequestration in coastal agroforestry; and soil biodiversity in regulating ecosystem functions and services.

In this book, emphasis has also been given to agroforestry analytical tools and approaches, frameworks, and policy. Eminent researchers explored the use of geospatial information systems for quantifying land potential and suitability mapping for agroforestry interventions; the rationale for promoting various agroforestry practices as climate-smart agricultural practices; advances to meet the commitments in Nationally Determined Contributions to the UNFCCC; and mainstreaming the potential of traditional AFS in national policy framework and global goals. The study design and statistical analysis of tree effects in agroforestry; the scope of integrating Moringa in agroforestry for adaptation and mitigation of climate change; and socioeconomic impacts and policy issues of small holders practicing agroforestry have also been emphasized. Authors also stressed the need for integrating agroforestry and climate-smart agriculture in policies, strategies, national plans, programs, and projects so as to achieve sustainable development goals.

This synthesis volume will certainly prove useful to scientists, researchers, educators, graduate and post-graduate students, developmental agents, extension workers, policy makers as well as the farming communities, businesspeople, and non-government organizations interested in harnessing benefits of agroforestry and expanding the horizon for human well-being.

We very much appreciate and acknowledge the commitment of all the contributors for the successful completion of this book series project. We are also grateful to the reviewers for their suggestions and critical comments, which greatly improved the clarity and content of the chapters. We are also grateful to the large number of individuals and institutions whose research publications, technical reports, and annual reports provided the much-needed information to the respective chapter authors of this book. We are thankful to Professor PKR Nair, Distinguished Professor of Agroforestry (Emeritus), University of Florida, Gainesville, Florida 32608, USA, for writing the Foreword and appreciations. We are highly indebted to Professor Rajeev K Varshney, Director, State Agricultural Biotechnology Centre; Director, Centre of Crop and Food Innovation; and International Chair in Agriculture and Food Security with Food Futures Institute, Murdoch University, Australia, for giving us this opportunity to participate in the Book Series Project "Sustainability Sciences in Asia and Africa." We thank all those who helped us directly and indirectly in the compilation of this very important publication.

New Delhi, India — Jagdish Chander Dagar
Kurukshetra, India — Sharda Rani Gupta
Addis Ababa, Ethiopia — Gudeta Weldesemayat Sileshi

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About the Editors

Jagdish Chander Dagar, Former Assistant Director General and Emeritus Scientist in ICAR, has been well recognized both nationally and internationally and grown professionally through his academic and research pursuit in the field of plant sciences, agriculture, ecology, and agroforestry. He has published more than 350 research papers in peer-reviewed journals, book chapters, and in proceedings of conferences/symposia. He has written and edited 20 books, published by reputed publishers. He has guided many research students for their project work and PhD degrees. He has diverse research interests in the field of agroforestry, management of natural resources, biosaline agriculture, judicious management of saline and poor quality waters, urban and peri-urban agriculture, rehabilitation of degraded lands including salt-affected and waterlogged soils, biodrainage, ethnobotany, plant ecology, environmental sciences, biodiversity, grazing lands and their management, halophytes including mangroves, climate change, sustainable intensification of agriculture and policy initiatives. Recognizing the research contributions, he was conferred with several awards and honors: Sajjad Memorial Gold Medal, Hari Om Asharam Trust Award of ICAR, Swami Pranavananda Saraswati National Award of UGC, CSSRI Excellence Award on Soil Salinity & Water Management, and Dr KG Tejwani Award for Excellence in Agroforestry Research & Development. Recently, Indian Society of Agroforestry has bestowed upon Dr Dagar the prestigious Life-Time Achievement Award for his immense contribution in Agroforestry Research and Management. Further, he is Fellow of National Academy of Agricultural Sciences, International Society of Tropical Ecology, Indian Botanical Society, National Institute of Ecology, Range Management Society of India, National Environmental Science Academy, Andaman Science Association, Indian Society of Soil Salinity & Water Quality; Honorary Fellow of Indian Society of Agroforestry; and Life Member of above societies and of Indian Society of Coastal Agricultural Research. He has also been consultant of several national and international agencies such as FAO of UN, CIMMYT, and Haryana Forest Department. Dr Dagar is the Chief Editor of *Journal of Soil Salinity and Water Quality* and a member of the Editorial Advisory Board of *Indian Journal of Agroforestry* and active in social services.

Sharda Rani Gupta, former Professor of Botany, Dean Life Sciences, and Emeritus Fellow of UGC, is a well-known ecologist nationally and internationally, who has served in the Department of Botany for the last 34 years and visiting faculty in the Institute of Environmental Studies at Kurukshetra University, Kurukshetra, India. Dr Gupta has made significant contribution towards better understanding biodiversity and ecosystem functioning of grassland and forest ecosystems, soil biodiversity, and ecological rehabilitation of salt-affected soils, carbon sequestration in agroforestry systems, and the sustainability of conservation agricultural systems. She has published more than 105 research papers in peer-reviewed national and international journals, as book chapters, and in proceedings; published four books in the field of ecology and agroforestry; successfully completed several funded research projects; guided the project work of 20 research students for their PhD degree. She has been associated with the Soil Science Department, Rothamsted Experimental Station, Harpenden, and Herts, UK, on Commission of European Communities Fellowship (1990–1991); a life member of several societies in India; and is a Fellow of the National Institute of Ecology, India. Dr Gupta is presently serving as Member of the People's Biodiversity Registers Quality Monitoring Committee of

Haryana State Biodiversity Board, associated with the Institute of Environmental Studies, and actively participates in socially relevant programs.

Gudeta Weldesemayat Sileshi has over 25 years of experience in agricultural research for development (R & D), research management, and teaching. He is currently Fellow of the African Academy of Sciences, Fellow of the Ethiopian Academy of Sciences, an Adjunct Professor at Addis Ababa University in Ethiopia, and formerly an Honorary Fellow at the University of KwaZulu-Natal in South Africa. He is currently the Regional Chief Editor (Africa) of *CABI Agriculture and Bioscience Journal*. Since 2017, he has also been Deputy Coordinator of Design, Performance and Evaluation of Experiments in the International Union of Forest Research Organizations (IUFRO). He was also a member of the Editorial Advisory Board of Forest Ecology and Management. He holds a BSc degree in Biology, MSc degree in Agriculture, and PhD degree in Ecology. Previously he worked as a Lecturer at the Alemaya University of Agriculture in Ethiopia (1987–1997), Research Associate at the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya (2000–2001), and a Scientist (2002–2011) at the World Agroforestry Centre (ICRAF) based in Zambia and Malawi. From 2011 to 2014 he was the regional representative of ICRAF for the southern Africa region, where he managed the *Malawi Agroforestry Food Security Program* and developed a vibrant multi-stakeholder R & D program called *Building a Large Evergreen Agriculture Network for Southern Africa* implemented in Malawi, Zambia, Mozambique, Botswana, and South Africa. He is one of the pioneers of the fertilizer tree system, an agroforestry technology tailored to counter land degradation, climate change impacts and improving productivity and food security in Africa. He has authored over 200 peer-reviewed papers in journals and book chapters. He has also coedited a book entitled *Indigenous Fruit Trees in the Tropics* in 2008 and coauthored two books entitled *Termite Management in Agroforestry* in 2016 and *Bamboo: Climate Change Adaptation and Mitigation* in 2020.

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Part I
Progress Towards Sustainable Intensification and Climate Change

Chapter 1
Introduction: Agroforestry for Sustaining the Global Agriculture in a Changing Environment

Jagdish Chander Dagar, Sharda Rani Gupta, and Gudeta Weldesemayat Sileshi

Abstract Agroforestry, as a subject of scientific investigation, assumes wider recognition in view of the need for sustainable intensification of agriculture to provide food to the ever-growing population, combating climate change and conserving biodiversity. The main objective of this book is to synthesize the relevant information from Africa and Asia for the stability, sustainability and diversification of agricultural production. In this book, various aspects of the emerging research areas of agroforestry in Asia and Africa regions have been discussed by eminent researchers and experts with a focus on climate change adaptation and mitigation, restoration of degraded landscapes, biodiversity and ecosystem services, modern agroforestry approaches and policy perspectives. This introductory chapter provides the background and sets the scene for the remaining chapters. With a total of 25 chapters, this compilation is structured into four sections, namely, progress towards sustainable intensification and climate change, landscape restoration and combating desertification, biodiversity and ecosystem services, and analytical approaches and policy perspective.

Keywords Intensification of agriculture · Landscape restoration · Combating desertification · Ecosystem services · Analytic approach · Policy initiatives

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1.1 Background

Globally, the human population is increasing unabated, and it is projected to reach 9.7 billion by 2050, which may require an increase in global food production substantially (Foley et al. 2005; Tilman et al. 2011). With the adoption of the Green Revolution in the 1960s, intensive agriculture involving the use of chemical fertilizers and pesticides, new crop varieties, modern irrigation, and farm mechanization had obvious impacts on farming systems and the agricultural landscapes (Garnett et al. 2013; Kanter et al. 2016; Bakış et al. 2021). However, most of the agricultural intensification was carried out without much consideration to environmental sustainability. The global food system is now one of the major drivers of global biodiversity loss (Ceballos et al. 2015; Chaudhary et al. 2018). A growing body of evidence also suggests that the current global food system is inadequate to meet the food and nutritional needs of the world population without compromising future well-being (Meybeck and Gitz 2017). A major transformation is needed in what food is consumed, how food is produced, processed, transported and distributed to meet the Sustainable Development Goals of United Nations ending hunger and malnutrition by 2030 (Wezel et al. 2020). The Food and Agricultural Organization of the United Nations (FAO) advocated 'Sustainable Intensification of agriculture' as a future strategy for addressing the challenges of growing population, food security, livelihood security, climate change, natural resource conservation (FAO 2017; Garnett et al. 2013) and the resilience of people, communities and ecosystems to the changing environment (FAO 2013). Over the years, a number of influential publications (Altieri et al. 2012; Barnes and Thompson 2014; Campbell et al. 2014, 2017; Cassman and Grassini 2020; Conway 1997; Gadanakis et al. 2015; Garnett et al. 2013; Tilman et al. 2011; Rockström et al. 2017) and policy documents (see Royal Society 2009) have recognized sustainable intensification as an approach to increase productivity on existing agricultural lands with positive environmental and social impacts. A truly sustainable intensification needs promotion of multifunctional landscapes, ensuring the ecological functions that underpin food production, biodiversity conservation and other ecosystem services (Holt et al. 2016).

By combining trees or other woody perennials with crops and livestock production systems, it is possible to achieve multi-functional landscapes that contributes to high-quality agricultural production, ecosystem services and biodiversity conservation (Pretty 2018; Torralba et al. 2016; Castle et al. 2021). As such, agroforestry is becoming increasingly important because of its multiple roles and services for biodiversity conservation, carbon sequestration, improved nutrient and water cycling, adaptation and mitigation of climate change and restoration of degraded landscapes (Van Noordwijk et al. 2021; Dagar et al. 2020a, b), besides meeting multiple socio-economic benefits, diversification of farm products and increasing agricultural productivity (Sileshi et al. 2008; Waldron et al. 2017; Rosenstock et al. 2019). Agroforestry for sustainable intensification is the key strategy for implementing the UN-Sustainable Development Goals across the production landscapes globally, particularly in Asia and Africa (United Nations 2015; van

Noordwijk et al. 2018; Waldron et al. 2017; Plieninger et al. 2020). In a systematic review, Castle et al. (2021) reported that in low- and middle-income countries, agroforestry interventions showed positive to neutral effects on agricultural productivity, income, nutrition and food security. However, there is an urgent need to examine multiple outcomes of agroforestry interventions for evidence-based policy and investment decisions to advance sustainable development goals (Castle et al. 2021).

This book will open up new vistas for sustainably intensifying agricultural production through agroforestry to provide food to the ever growing population in developing countries, as well as addressing land degradation and biodiversity loss. In this introductory chapter, the key issues covered in this compilation are briefly described below in order to set the scene for the remaining chapters.

1.2 Sustainable Intensification and Climate Change

The food system has become increasingly globalized and trade-dependent due to the demographic weight of urbanization, which is expected to rise from 55% of current population to nearly 70% by 2050 (Cassman and Grassini 2020). As such, markets and policies drive land use changes and input use at the individual farm and regional scales. There has been a growing emphasis on the delivery of private goods to ensure food is produced cheaply (Holt et al. 2016) not at the expense of the environment. For example, increases in global production of major crops have come largely from area expansion. Recent estimates suggest that 85%, 66%, 43% and 17% of the increase in global soybean, maize, rice and wheat production, respectively, has come from area expansion compared to yield gains on existing crop land (Cassman and Grassini 2020) and in Sub-Saharan Africa, 91–98% of the increase in maize, cassava, beans and soybean production has been achieved through an increase in area (Kuyah et al. 2020). The negative impacts of land use practices of converting rainforests, grasslands, savannahs and wetlands for agricultural expansion on ecosystem services and the biodiversity, which are public goods, are often ignored. Recently, Simkin et al. (2022) projected the growing impact of urban expansion on biodiversity of mammals, birds, reptiles and amphibians from 2015 to 2050. Urbanization has also been identified as a serious driver of biodiversity loss comparable to that of agriculture and forestry (Simkin et al. 2022; Laurance and Engert 2022).

The trade-offs between food production and other ecosystem services are rarely considered in decisions regarding land use change (e.g. clearing forests for agricultural use) or using fertilizers, pesticides and other inputs. As a result, land use change for agriculture alone is responsible for over 60% of the terrestrial biodiversity loss, 24% of greenhouse gas emissions and 33% of soil degradation (Ceballos et al. 2015; Chaudhary et al. 2018).

The definition of sustainable intensification has been evolving. Godfray et al. (2010) define sustainable intensification as the process of producing more food from the same area of land while reducing the environmental impacts. Pretty and

Bharucha (2014) define sustainable intensification as a process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land. According to the Commission on Sustainable Agriculture Intensification (CoSAI), sustainable agricultural intensification is defined as the transformative changes in agriculture that are urgently required to meet rapidly increasing global needs for affordable, nutritious, safe and healthy food, while protecting and improving the natural environment, and reducing poverty and social exclusion (https://wle.cgiar.org/cosai/).

Given these trajectories, the projected food demand will not be met without further expansion of agriculture and clearance of forests. Using satellite imagery, Curtis et al. (2018) showed that 27% of all forest loss was because of permanent commodity-driven deforestation to grow commodity crops in Latin America and Southeast Asia. Food security has also become increasingly uncertain under future climate change (Global Food Security Programme 2015). According to new research, the probability of weather hazards occurring at the same time in the world's major breadbaskets can increase the risk of collapse of the global food system including wheat, maize, rice and soybean crops (Abson et al. 2020; Gaupp et al. 2020; Mehrabi and Ramankutty 2019). For example, there is an increasing risk of simultaneous failure of wheat, maize, rice and soybean crops across the breadbaskets (Gaupp et al. 2020).

There is growing interest in agroforestry as part of sustainable intensification initiatives for the stability of agricultural production, and improving ecosystem services (FAO 2013; Pretty 2018; Cardinael et al. 2021). About 43% of all agricultural land in the world in the year 2010 was under some kind of agroforestry with at least 10% tree cover (Zomer et al. 2016). Globally, it is estimated that agroforestry systems occupy about 1 billion hectares of land; more than 1.2 billion people depend directly on agroforestry practices, products and services in rural and urban areas. Agroforestry encompasses a complex set of practices, and there are multiple ways of classifying these practices (Mbow et al. 2014; Atangana et al. 2014; Shin et al. 2020; Nair 1985; Nair et al. 2021) at scales varying from plot-level to multi-functional landscapes, and the interface of agricultural and forestry policies. Adaptation to climate change is now inevitable, and outputs from research on agroforestry have become instrumental for adaptation to climate change and as buffer against climate variability. Multi-purpose agroforestry has provided several opportunities for adaptation in Vietnam as tree-based systems were less affected by climate shocks than rice- and rain-fed crops (Nguyen et al. 2013).

Climate change and variability and biodiversity loss will impact food and fibre production around the world due to the effects on plant growth and yield by elevated CO_2, higher temperatures, altered precipitation and transpiration regimes, and increased frequency of extreme events, as well as modified weed, pest and pathogen pressure (Tollefson 2021; IPCC 2021). Due to temperature rise in the future, extreme weather events will become increasingly severe, an extreme temperature event that occurred once every 50 years in centuries in the past will probably occur every 3–4 years (IPCC 2021). Many developing countries, particularly Asia and Africa, are vulnerable to climate change which is affecting agricultural production. Climate change may also lead to increased land degradation, reduction in crop yields of staple crops and increase in the incidence of pests and diseases (Sheppard et al. 2020). Agroforestry can play a key role both for the adaptation and the mitigation of climate change (Syampungani et al. 2010; Nair 2012; Catacutan et al. 2017; Zomer et al. 2016; Dhyani et al. 2021; Cardinael et al. 2021), as well as for greening the landscapes in urban areas.

1.3 Agroforestry for Land Restoration

The International Platform for Biodiversity and Ecosystem Services reported that more than 25% of Earth's land areas are severely degraded, which is adversely impacting the well-being of 3.2 billion people globally, especially smallholder farmers and rural communities (IPBES 2018). Unsustainable agriculture practices are the major contributors of the loss of fertile soils, besides emitting greenhouse gases to the atmosphere.

The UN Decade on Ecosystem Restoration (2021–2030) aims to halt the degradation of ecosystems, and to enhance livelihoods, counteract climate change and biodiversity loss (United Nations 2019; Farrell et al. 2021). Large-scale restoration of ecosystems can play a key role in mitigating climate change and species extinction. The major international conventions (e.g. CBD, UNFCCC, Ramsar), intergovernmental programmes (e.g. IUCN, UNEP, UNCCD), and international platforms (e.g. IPBES) as well as the 2015 UN Sustainable Development Goals (SDGs) have recognized large-scale restoration as a global priority for biodiversity conservation, combating desertification and land degradation, and limiting the impacts of anthropogenic climate change. The Bonn Challenge pledges to restore 350 million hectares of degraded land by 2030. In addition to ambitious global initiatives, there are numerous regional initiatives like the Great Green Wall, an African-led movement and the Global Mangrove Alliance (Mansourian and Berrahmouni 2021; Valderrábano et al. 2021). Agroforestry practices have great potential for restoring degraded landscapes, and achieving land net degradation neutrality (LDN) by 2030 as set by the United Nations Convention to Combat Desertification (UNCCD).

Ecosystem restoration is a broad concept that constitutes a continuum of restorative actions that combine human activities and interventions as well as ecological solutions to reverse ecosystem and landscape degradation (Gann et al. 2019). However, full restoration of all ecosystems to a baseline is not feasible keeping in view the demands to maintain intensively managed agricultural and urban systems for human society (Science Task Force for the UN Decade on Ecosystem Restoration 2021). Ecosystem restoration remains among the most effective strategies to restore soil fertility and prevent species extinction (Newmark et al. 2017) and mitigate climate change (Bastin et al. 2019), there is a large potential for agroforestry and urban forestry in mitigating climate change.

Agroforestry practices suitable for degraded lands in Asia include long rotational fallows for soil conservation, home gardens, boundary plantings, perennial crops, hedgerow intercropping and live fences (FAO 2021). In different regions of Africa, shifting cultivation, rotational woodlot system, improved tree fallows, home gardens, parkland systems and silvopastoral systems represent some common agroforestry practices on degraded lands (see Dagar et al. 2020a, b). Agroforestry can add a high level of diversity on degraded lands besides supporting numerous ecological and production services for increased resilience to climate change impacts (Verchot et al. 2007; Schoeneberger et al. 2012). The mixing of woody plants into crop, forage and livestock production systems on degraded lands provides greater resilience to the inter-annual variability through crop diversification as well as through increased resource-use efficiency (Olsson et al. 2019).

1.4 Agroforestry for Biodiversity Conservation and Ecosystem Services

During the last two decades, agroforestry for biodiversity conservation has been receiving increased attention of researchers (see McNeely and Schroth 2006; Udawatta et al. 2019, 2021). Recent studies, reviews, meta-analysis and other reports from different regions of the world suggest that agroforestry systems have greater diversity as compared to monocropping systems and even higher than that of forests in some regions (Murdiyarso et al. 2002; Bhagwat et al. 2008; Barrios et al. 2018; Torralba et al. 2016; Niether et al. 2020). In a meta-analysis, Bhagwat et al. (2008) reported 60% greater mean richness of taxa in agroforestry than forests.

Greater biodiversity in agroforestry systems could be attributed to food, shelter, habitat, protection, refuge, favourable microclimate, improved soil–plant–water relationships and other resources provided by multi-species vegetation of AFS (Udawatta et al. 2019). Agroforestry has the potential to contribute to biodiversity conservation in agricultural landscapes by increasing structural complexity, and enhancing habitat and landscape heterogeneity (Torralba et al. 2016; Haggar et al. 2019). Studies have shown that agroforestry systems can increase the diversity of plants, vertebrates and arthropods (Clough et al. 2011; Dawson et al. 2013), and improve soil biodiversity (Barrios et al. 2012; Cardinael et al. 2020; Marsden et al. 2020). Recently, biodiversity patterns and strategies for biodiversity conservation in agroforestry systems have been analysed by using the Habitat Amount Hypothesis (Santos et al. 2022). This study has shown that agroforestry systems show higher structural complexity, functional diversity and overall biodiversity within diverse biogeographic regions and management types (Santos et al. 2022).

Ecosystem services are the benefits that the natural environment provides to the people; four major types of ecosystem services have been identified, namely, provisioning services, regulating services, cultural services and supporting services that contribute to human well-being (Costanza et al. 1997; Daily 1997). Studies have shown that the adoption of agroforestry can increase yields by an average factor of 1.96 (Pretty and Bharucha 2014), depending on crop type, local conditions and level of expertise (Garrity et al. 2010; Pretty and Bharucha 2014). The various regulating environmental services provided by agroforestry include enhanced soil fertility, reducing erosion in tropical regions, regulating water regimes for rural producers and urban consumers, biodiversity conservation and providing habitat for pollinators and seed dispersers, and climate regulation. Regulating ES tended to perform better in agroforestry landscapes.

Torralba et al. (2016) found that European agroforestry systems exert a significant positive effect on biodiversity conservation and ES provision compared to conventional systems, specifically concerning nutrient cycling, biodiversity conservation, and erosion control. Agroforestry systems can improve the provision of ecosystem services at the farm scale, thereby playing an important role in the sustainable intensification of agriculture (Marais et al. 2019). The strategic use of home gardens and boundary planting can play an important role for conserving tree diversity, and carbon storage, mitigating climate change in Ethiopian dryland ecosystems (Manaye et al. 2021).

The home gardens of Barak valley, Assam, India, are a reservoir of crop and other economic plant diversity for future use (Das and Das 2005), whereas homestead across Terai and Midhills of Nepal show an intensive cultivation of cereals, vegetable and species, vegetables and spices, perennial crops (timber, poles, fodder and fruit trees), grasses and animals (Amatya et al. 2018). The tropical home gardens in Sri Lanka and West Jawa are characterized by high species richness of plants (Kumar and Nair 2007). The greater diversity of birds and insect in agroforestry stems provides the beneficial service of pest reduction to adjacent crops (Gillespie et al. 1995). There is high plant diversity in home gardens of the coastal regions of India (see Kumar et al. 2022) and Southeast Asia (Abdoellah et al. 2006).

In Africa and Asia, the agroforestry systems and conservation farming lead to improvement of soil biodiversity (Sileshi et al. 2020; Mulia et al. 2021; Barrios et al. 2012; Kamau et al. 2020). Barrios et al. (2012) reported that agroforestry systems consistently exhibited substantial increases in the mean abundance of all groups of soil fauna compared to the continuous cropping. Agroforestry systems have been shown to increase abundance, biomass and diversity of earthworms compared to monocropping (see Rahman et al. 2012).

1.5 Tools and Policy for Promoting Agroforestry for Combating Climate Change

Agroforestry is a climate change mitigation solution as it can remove significant amounts of GHGs from the atmosphere. Promoting agroforestry is included in a large number of REDD+ and restoration programmes and projects in Africa and Latin America with a focus on forest-centric goals (Verchot et al. 2018). Crop lands currently store 3.07 Pg of carbon (C) in aboveground woody biomass (i.e., trees) and pasture lands account for an additional 3.86 Pg C across a combined 3.76 billion ha globally (Chapman et al. 2020). Therefore, many countries can meet large portions of their NDCs through the addition of trees in agricultural lands.

The availability of large data sets, remote sensing and Geographic Information Systems provide insights for the planning and management of land, particularly in agroforestry suitability assessment (Chiemela et al. 2018; Ahmad et al. 2021; Nath et al. 2021). By using multi-criteria evaluation modelling and GIS, Nath et al. (2021) showed that in the eastern Indian Himalayan region, ~77% of the region's arable land has very good to good suitability for agroforestry, which can further be improved by managing soil fertility and application of soil and water conservation measures. Remote sensing has revealed the suitability of different regions for agroforestry, indicating that India alone can increase its agroforestry by 2.7 times of the existing levels (Ahmad et al. 2021). In another study, Ahmad et al. (2020) combined land, soil, climate and topography data using the Food and Agriculture Organization (FAO) suitability criteria to measure land that can be used for agroforestry in south Asia.

Comprehensive analysis revealed that 69% of the total geographical area has more than 55% suitability for agroforestry. Thus, land suitability analysis helps planning the agroforestry interventions and scaling which further assists in building resilient landscapes for sustainable agricultural production systems, livelihoods and supporting sustainable development goals (Ahmad et al. 2020). On the basis of Sentinel-2 images from the period of 2017 to 2019. Lu et al. (2022) showed that tree cover in Parkland agroforestry systems of West Africa is dominated by *Faidherbia albida*, which contributes various benefits to local people.

1.6 Outline of the Book

In the following chapters, various aspects of the emerging research areas of agroforestry have been explored by eminent researchers and experts with a focus on climate change adaptation and mitigation, restoration of degraded landscapes, biodiversity and ecosystem services, modern agroforestry approaches and policy perspectives; accordingly, this compilation is structured into four sections.

Chapters 1–4 in section I of the book examined the progress toward sustainable intensification in the face of climate change in Africa and Asia. In Chap. 1, Dagar et al. describe in brief the potential of agroforestry systems for sustainable intensification of agriculture, ecosystem restoration for improving biodiversity, ecosystem services and carbon sequestration; the role of agroforestry in biodiversity conservation and ecosystem services, and modern approaches for analysing agroforestry systems and the challenges for policy formulation and implementation for achieving sustainable development goals. In Chap. 2, Van Noordwijk et al. have explored the extent to which agroforestry can match the evolving climate change mitigation and adaptation agenda in Asia and Africa. The authors argue that creating space for a continuum approach to agriculture, forestry and other land uses, within which trees outside forest and agroforestry can play an important role in climate change mitigation and adaptation. The authors further stressed the need for establishing stronger links across the vertical (individuals, communities, subnational, national and global) scale and the issue-cycle (data, feedbacks, institutions and goals) as part of complex, adaptive social-ecological systems. The challenge is how agroforestry policies integrate the interests of different stakeholders comprising farmers, corporate sectors and consumers along the supply chain. Kuyah et al. (Chap. 3) describe the Farmer Managed Natural Regeneration in Africa. The authors highlight challenges faced by dryland communities in Africa under changing environment and the strategies have been discussed for transforming drylands into productive, profitable and sustainable ecosystems that contribute to climate change adaptation and mitigation. As viable restoration practices for agricultural land across Africa, the adoption of Farmer Managed Natural regeneration (FMNR) techniques can increase agricultural yields, firewood availability, income and production diversity in drylands of Niger, the West African Sahel.

In recent years, there is growing interest in urban and peri-urban agriculture, forestry and agroforestry for reducing vulnerability to climate change (Lee-Smith 2010; Prain et al. 2010; Lwasa et al. 2015). A major challenge was created by the COVID-19 pandemic in availability of fresh and nutritious food at affordable prices to large and growing urban population. In Chap. 4, Dagar et al. discuss the role of home gardens, fodder banks and horticulture-based agroforestry in urban and peri-urban areas for providing food and nutritional security and improving the environment; sequestering carbon and enhancing environmental services.

In Section II, Chaps. 5–9 explore the role that agroforestry can play in landscape restoration and combating desertification. Gupta et al. (Chap. 5) have described that agroforestry can restore degraded lands by re-establishing ecological processes, structures and ecosystem functions. The authors have further provided evidence to show that agroforestry practices can provide an array of ecosystem services including provision of food, wood energy, improved soil fertility and enhancement of local climate conditions in degraded landscapes. Ecosystem restoration through agroforestry provides resilience by increasing crop yields, improved micro-climate and water regulatory services, control of soil erosion and improved soil fertility/nutrient use efficacy. Sileshi et al. (Chap. 6) have explored opportunities and challenges for integration of dryland agroforestry in large programmes such as the Great Green Wall initiatives to mitigate desertification. The authors argue that the wider adoption of agroforestry may not only solve local land degradation problems but it can also help in tackling global health and environmental challenges caused by desertification. They call for greater investment in agroforestry as a mitigation measure, and emphasize that investments should be pursued from local governments of distant megacities that are affected by desert dust annually.

In Chap. 7, Ortiz et al. have demonstrated that silvopastoral systems represent the main land uses for rehabilitation and reclamation of degraded lands and reducing C emissions from soil by promoting the formation of soil organic matter and increasing soil carbon, enhancing soil quality and improving ecosystem services. In this review, the authors have identified 25 major mechanisms responsible for soil organic matter, soil quality and carbon emission offset in silvopastoral systems. Yadav et al. (Chap. 8) explored opportunities for utilization of saline and other poor-quality waters in agroforestry to sustain production. Authors have given an overview of the salt-induced land degradation, discussed in detail the agroforestry interventions to rehabilitate salt-affected and waterlogged degraded landscapes with examples from Asia and Africa. They also briefly discussed soil bio-amelioration, carbon sequestration in plant biomass, soil carbon sequestration and climate change mitigation and adaptation in agroforestry systems on salt-affected lands. Dhakal and Rai in Chap. 9 have documented the prevalent agroforestry systems in Nepal and highlighted the contribution of these systems to landscape restoration, climate change mitigation and disaster risk reduction. The authors also highlighted the key constraints to agroforestry promotion in Nepal including ambiguous policies, lack of institutions, small landholdings and lack of market infrastructure.

The third part of the book, including Chaps. 10–16, deals with the role of agroforestry in biodiversity conservation and enhancing ecosystem services. Biodiversity plays pivotal role in the provision of ecosystem goods and services, but the services are being eroded by anthropogenic disturbances. Asian and African countries are experiencing large-scale biodiversity loss due to rapid conversion of forests to cropland, human settlement, infrastructure and industrial developments. This has brought also wildlife into conflict with humans. The case of human conflicts with Asian and African elephants as an obvious example has been included in Chap. 10 by Rahman et al. who explored the role of agroforestry systems for enhancing biodiversity and provision of ecosystem services in agricultural landscapes in Southeast Asia. The authors provide substantive evidence that agroforestry systems can conserve species diversity and enhance ecosystem services. They argue that careful agroforestry design will not only increase the multiple ecosystem functions but can also create corridors and buffer zones to support natural habitats, and to reduce human and wildlife conflict with case study of Asian elephants.

Chapter 11 by Sileshi et al. gives evidence based on domestication and management of indigenous fruit trees in enhancing nutrition, income and biodiversity in Africa. They have enumerated the most preferred species, and discuss challenges and opportunities for their domestication and research needs. Chapter 12 contributed by Reang and co-workers gives an account of the plant diversity and its management and conservation in ethnic homestead gardens in the tropical regions of Asia and Africa. The authors emphasize their recognition in development initiatives and formulation of appropriate policies for conservation and better utilization of the genetic materials conserved in these homesteads by ethnic communities and preserving the indigenous knowledge associated with homestead gardens.

Ahamad et al. in Chap. 13 explored the role of agroforestry for plant diversity and livelihood security in Southwest Asia as many multi-purpose forest trees with food, timber, medicinal and industrial values have been introduced in different agroforestry systems; authors further discuss the future scope of agroforestry practices such as wind breaks and shelter belts, riparian forest buffers, alley cropping and forest farming in Southwest Asia.

The island and coastal regions are often described as the cradle of agroforestry in recognition of their long history of numerous traditional practices under diverse agroecological conditions based on indigenous knowledge (Dagar et al. 2014, 2020a). Kumar et al. in Chap. 14 have highlighted the importance of plantation-based multi-storied integrated cropping systems, home gardens, farming in forests, fodder farming on neglected coconut plantations, multi-purpose trees and shrubs on farm lands, site-specific systems for saline and waterlogged conditions, alley cropping and mangrove-based systems to protect coastlines. These workers emphasized the role played by the coastal agroforestry in biodiversity conservation, livelihood security, carbon sequestration and meeting some of the important sustainable development goals, with special reference to India and Southeast Asia.

Chapter 15 by Devi et al. provides an overview of the biodiversity and ecosystems services of agroforestry systems of the Himalayan region. The provisioning and regulating services provided by different agroforestry systems are discussed; the potential of agroforestry for the mitigation of climate change through carbon sequestration in plant biomass and soil are also highlighted. Gupta et al. (Chap. 16) give an overview of the role of agroforestry in improving soil biodiversity, soil ecosystem functions and services, and litter decomposition processes in the agroforestry systems of sub-Saharan Africa and Asia. The authors show that diverse plant communities can modify the important soil functions, with possible feedback to the above- and below-ground interactions in the case of both tree and crops. The authors also provide documentary evidence indicating that agroforestry systems are highly efficient in improving soil biodiversity and litter decomposition processes leading to increase in the crop yield and sequestration of atmospheric carbon dioxide. The need has also been emphasized for long-term studies on diversity of soil fauna and microorganisms, and soil ecosystem functions for a greater understanding of seasonal, short-term and long-term effects of agroforestry systems.

In documentation of agroforestry research, use of analytical approaches and modern tools is very important for authentication of the evidence provided to prove its applicability in the field. Further, policy initiatives at all levels and their implementation are important for the success of any programme. In part IV, Chaps. 17–25 present agroforestry analytical approaches, frameworks and policy perspectives. Ahmad et al. (2021) stated that land suitability analysis helps planning the agroforestry interventions and scaling up for sustainable agricultural production systems, livelihoods and supporting sustainable development goals. In Chap. 17, Rizvi et al. explore the use of geospatial information systems (GIS) for quantifying land potential and suitability mapping for agroforestry interventions. The authors argue that land suitability analysis (LSA) and GIS can be harnessed for the planning and management of land and judicious application of agroforestry.

FAO recognizes agroforestry as a climate-smart practice contributing to climate change mitigation and its capacities in adapting to climate change and values its potential to improve food security. Since the Paris Agreement of 2015, the Nationally Determined Contributions (NDCs) represent the main instrument for defining, communicating and potentially reporting contributions of countries to long-term climate goals of the UNFCCC. Chapter 18 (Sileshi et al.) have synthesized the evidence and rationale for promoting various agroforestry practices as climate-smart agricultural practices. Agroforestry practices provide productivity, adaptation and mitigation benefits through their impact on microclimate and improvement in water use efficiency.

Chapter 19 by Duguma et al. demonstrates the potential of agroforestry to meet the commitments set out in Nationally Determined Contributions to the UNFCCC. The authors show that 80% of the non-Annex I countries could achieve their unconditional commitments by converting just about 25% of deforested areas to agroforestry. In Chap. 20, Shukla and Dhyani have documented the potential of traditional agroforestry systems for intensification of agriculture and meeting the sustainable development goals (SDGs) with lessons from Asia and Africa. The authors emphasized that there is need to mainstream the potential of traditional AFS in their national policy framework to create greater synergy with the biodiversity, climate and restoration targets and goals.

In Chap. 21, Sileshi and Nath provided a framework for analysing spatial patterns and extent of influence by single trees on ecosystem properties in agroforestry. Using 36 datasets collected from sites across the globe, the authors show that single-tree effects are monotonically decreasing functions of distance from the tree trunk. The power-law distance-decay model described lateral root density, hydraulic conductivity, soil organic carbon concentrations, nutrient pools, crop yields and biomass of understorey vegetation. The patterns elucidated in this analyses provide a theoretical justification for a paradign "shift" in study design and statistical analysis of tree effects in agroforestry.

Chapter 22, contributed by Bania et al., explored opportunities for integrating *Moringa* in agroforestry for adaptation and mitigation of climate change in Asia and Africa. Based on review of studies, authors concluded *M. oleifera* and *M. stenopetala* trees have the potential to provide food and nutritional security in tropical regions of Asia and Africa besides their use in water treatment, biofuel production, agriculture and climate change mitigation. In Chap. 23, Nath et al. have argued that the payment for ecosystem services can be a good mechanism to incentivize farmers to preserve forest patches on their land through agroforestry interventions or converting degraded cropland into agroforestry systems. The authors emphasized that poor institutional readiness and lack of mechanisms to reward farmers/land managers are among critical issues that need to be addressed.

The industrial agroforestry has received increasing attention and attraction among the industries, tree growing farmers, bureaucrats and policy makers due to its role in extending provisional, regulating, cultural and supporting services. Parthiban et al. (Chap. 24) conceived a value chain on industrial agroforestry model and implemented successfully with increased participation of all stakeholders. This model has identified wide range of challenges and constraints along with research gaps that existed in the entire Production to Consumption System in agroforestry that can be resolved through technological, organizational and marketing interventions.

In the synthesis (Chap. 25), Sileshi et al. highlight the key messages, challenges, ecological and socio-economic impacts and policy issues of traditional and modern agroforestry in Asia and Africa.

Thus, this book, in its totality, presents a wide range of topics and agroforestry approaches from different agroecological and geographic locations for sustainable intensification of agriculture in the face of climate change in two agriculturally important continents of Asia and Africa, where food security and climate change issues are critical. The knowledge on emerging aspects of climate change, biodiversity conservation, environmental services, restoration of degraded lands, innovations in modern agroforestry and the interface of research and policies has been synthesized. This publication will serve as a useful reference book for researchers, students, entrepreneurs, conservation agencies and policy makers engaged in the promotion of agroforestry research and development.

References

Abdoellah OS, Hadikusumah HY, Takeuchi K, Okubo S (2006) Commercialization of homegardens in an Indonesian village: vegetation composition and functional changes. Agrofor Syst 68:1–13

Abson DJ, Chappell MJ, Hanspach J, Mikulcak F, Tichit M, Fischer J, Mehrabi Z (2020) Food system collapse. Nat Clim Chang 10:16–17

Ahmad F, Uddin MM, Goparaju L, Rizvi J, Biradar C (2020) Quantification of the land potential for scaling agroforestry in South Asia. KN J Cartogr Geogr Inf 70:71–89

Ahmad F, Uddin MM, Goparaju L, Talukdar NR, Rizvi J (2021) Agroforestry environment, potentiality and risk in India: a remote sensing and GIS understanding. Environ Dev Sustain 23:15183–15203

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13

Amatya SM, Cedamon E, Nuberg I (2018) Agroforestry systems and practices. Agriculture and Forestry University, Rampur, p 108

Atangana A, Khasa D, Chang S, Degrande A (2014) Definitions and classification of agroforestry systems. Tropical agroforestry. Springer, Cham

Bakış ALP, Macovei I, Barros P, Gomes C, Carvalho D, Cabral JA et al (2021) Is biodiversity linked with farm management options in vineyard landscapes? A case study combining ecological indicators within a hybrid modelling framework. Ecol Indic 121:107012

Barnes AP, Thompson ST (2014) Measuring progress towards sustainable intensification: how far can secondary data go? Ecol Indic 36:213–220

Barrios E, Sileshi GW, Shepherd KD, Sinclair F (2012) Agroforestry and soil health: linking trees, soil biota and ecosystem services. In: Wall DH (ed) The Oxford handbook of soil ecology and ecosystem services. Oxford University Press, Oxford, pp 315–330

Barrios E, Valencia V, Jonsson M, Brauman A, Hairiah K, Mortimer PE et al (2018) Contribution of trees to the conservation of biodiversity and ecosystem services in agricultural landscapes. Int J Biodivers Sci Ecosyst Serv Manage 14:1–16

Bastin JF, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner CM, Crowther TW (2019) The global tree restoration potential. Science 365:76–79

Bhagwat SA, Willis KJ, Birks HJB, Whittaker RJ (2008) Agroforestry: a refuge for tropical biodiversity? Trends Ecol Evol 23:261–267. https://doi.org/10.1016/j.tree.2008.01.005

Campbell BM, Thornton PK, Zougmoré R, van Asten P, Lipper L (2014) Sustainable intensification: what is its role in climate smart agriculture? Curr Opin Environ Sustain 8:39–43

Campbell BM, Beare DJ, Bennett EM, Hall-Spencer JM, Ingram JSI, Jaramillo F, Ortiz R, Ramankutty N, Sayer JA, Shindell D (2017) Agriculture production as a major driver of the earth system exceeding planetary boundaries. Ecol Soc 22:8

Cardinael R, Mao Z, Chenu C, Hinsinger P (2020) Belowground functioning of agroforestry systems: recent advances and perspectives. Plant Soil 453:1–13

Cardinael R, Cadisch G, Gosme M, Oelbermann M, van Noordwijk M (2021) Climate change mitigation and adaptation in agriculture: why agroforestry should be part of the solution. Agric Ecosyst Environ 319:107555

Cassman KG, Grassini P (2020) A global perspective on sustainable intensification research. Nat Sust 3:262–268

Castle SE, Miller DC, Ordonez PJ, Baylis K, Hughes K (2021) The impacts of agroforestry interventions on agricultural productivity, ecosystem services, and human well-being in low- and middle-income countries: a systematic review. Campbell Syst Rev 17:e1167

Catacutan DC, van Noordwijk M, Nguyen TH, Öborn I, Mercado AR (2017) Agroforestry: contribution to food security and climate-change adaptation and mitigation in Southeast Asia. White Paper. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program; Jakarta, Indonesia: ASEAN-Swiss Partnership on Social Forestry and Climate Change

Ceballos G et al (2015) Accelerated modern human–induced species losses: entering the sixth mass extinction. Sci Adv 1:e1400253

Chapman M, Walker WS, Cook-Patton SC, Ellis PW, Mary F, Griscom BW, Baccini A (2020) Large climate mitigation potential from adding trees to agricultural lands. Glob Chang Biol 26: 4357–4365

Chaudhary A, Gustafson D, Mathys A (2018) Multi-indicator sustainability assessment of global food systems. Nat Commun 9:848

Chiemela SN, Noulekoun F, Zenebe A (2018) Transformation of degraded farmlands to agroforestry in Zongi Village, Ethiopia. Agrofor Syst 92:1317–1328

Clough Y, Barkmann J, Juhrbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darras K, Putra DD, Erasmi S, Pitopang R, Schmidt C, Schulze CH, Seidel D, Steffan-dewenter I, Stenchly K, Vidal S, Weist M, Wielgoss AC, Tscharntke T (2011) Combining high biodiversity with high yields in tropical agroforests. Proc Natl Acad Sci U S A 108:8311–8316

Conway G (1997) The doubly green revolution. Penguin, London

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Curtis PG, Slay GM, Harris NL, Tyukavina A, Hansen MC (2018) Classifying drivers of global forest loss. Science 361:1108–1111

Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Agroforestry systems in India: livelihood security & ecosystem services. Springer, New Delhi, pp 185–232

Dagar JC, Gupta SR, Teketay D (eds) (2020a) Agroforestry for degraded landscapes. Recent advances and emerging challenges, vol I. Springer, Singapore

Dagar JC, Gupta SR, Teketay D (eds) (2020b) Agroforestry for degraded landscapes. Recent advances and emerging challenges, vol II. Springer, Singapore

Daily GC (1997) Nature's services: societal dependence on natural ecosystems. Island, Washington

Das T, Das AK (2005) Inventorying plant biodiversity in homegardens: a case study in Barak Valley, Assam, North East India. Curr Sci 89:155–163

Dawson IK, Guariguata MR, Loo J, Weber JC, Lengkeek A, Bush D, Cornelius J, Guarino L, Kindt R, Orwa C, Russel J, Jamnadass RH (2013) What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, in situ and ex situ settings? A review. Biodivers Conserv 22(2):301–324

Dhyani S, Murthy IK, Kadaverugu R, Dasgupta R, Kumar M, Adesh Gadpayle K (2021) Agroforestry to achieve global climate adaptation and mitigation targets: are south Asian countries sufficiently prepared? Forests 12:303

FAO (2013) Resilient livelihoods—disaster risk reduction for food and nutrition security framework programme. Food and Agriculture Organization of the United Nations, Rome

FAO (2017) Sustainable intensification of agriculture. http://www.fao.org/policy-support/policy-themes/sustainable-intensification-agriculture/en/. Accessed 13 July 2017
FAO (2021) State and outlook of agroforestry in ASEAN: status, trends and outlook 2030 and beyond. Food and Agriculture Organization of the United Nations, Bangkok
Farrell CA, Aronson J, Daily GC, Hein L, Obst C, Woodworth P, Stout JC (2021) Natural capital approaches: shifting the UN decade on ecosystem restoration from aspiration to reality. Restor Ecol 2021:e13613. https://doi.org/10.1111/rec.13613
Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT et al (2005) Global consequences of land use. Science 309:570–574
Gadanakis Y et al (2015) Evaluating the sustainable intensification of arable farms. J Environ Manag 150:288–298
Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J, Hua F, Echeverría C, Gonzales E, Shaw N, Decleer K, Dixon KW (2019) International principles and standards for the practice of ecological restoration. Restor Ecol 27: S1–S46. https://doi.org/10.1111/rec.13035
Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HCJ (2013) Sustainable intensification in agriculture: premises and policies. Science 341(6141):33–34. https://doi.org/10.1126/science.1234485
Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A et al (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Secur 2: 197–214
Gaupp F, Hall J, Hochrainer-Stigler S, Dadson S (2020) Changing risks of simultaneous global breadbasket failure. Nat Clim Chang 10:54–57
Gillespie AR, Miller BK, Johnson KD (1995) Effects of ground cover on tree survival and growth in filter strips of the Corn Belt region of the Midwestern US. Agric Ecosyst Environ 53:263–270
Global Food Security Programme (2015) UK–US taskforce on extreme weather and global food system resilience. Extreme weather and resilience of the global food system final project report
Godfray HC, Beddington JR, Crute IR et al (2010) Food security the challenge of feeding 9 billion people. Science 327:812
Haggar J, Pons D, Saenz L, Vides M (2019) Contribution of agroforestry systems to sustaining biodiversity in fragmented forest landscapes. Agric Ecosyst Environ 283:106567. https://doi.org/10.1016/j.jenvman.2019.109504
Holt AR, Alix A, Thompson A, Maltby L (2016) Food production, ecosystem services and biodiversity: we can't have it all everywhere. Sci Total Environ 573:1422–1429
IPBES (2018) Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, IPBES Secretariat, p 44
IPCC (2021) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Kamau S, Barrios E, Karanja NK, Ayuke FO, Lehmann J (2020) Dominant tree species and earthworms affect soil aggregation and carbon content along a soil degradation gradient in an agricultural landscape. Geoderma 359:113983. https://doi.org/10.1016/j.geoderma.2019.113983
Kanter DR, Schwoob M-H, Baethgen WE, Bervejillo JE, Carriquiry M, Dobermann A, Ferraro B, Lanfranco B, Mondelli M, Penengo C, Saldias R, Silva ME, de Lima JMS (2016) Translating the sustainable development goals into action: a participatory backcasting approach for developing national agricultural transformation pathways. Glob Food Secur 10:71–79
Kumar BM, Nair PKR (2007) Tropical homegardens: a time-tested example of sustainable agroforestry. Springer, Dordrecht
Kumar P, Uthappa AR, Chavan SB, Chichaghare AR, Debta H, Bhat S, Dagar JC (2022) Achieving biodiversity conservation, livelihood security and sustainable development goals through

agroforestry in coastal and island regions of India and South East Asia. In: Dagar JC, Gupta SR, Sileshi GW (eds) Agroforestry for intensification of agriculture in Asia and Africa. Springer, New York

Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Kuntashula E, Dimobe K, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes-recent advances and emerging challenges, vol 1. Springer, Singapore, pp 135–167

Laurance WF, Engert J (2022) Sprawling cities are rapidly encroaching on Earth's biodiversity. Proc Natl Acad Sci U S A 119:e2202244119

Lee-Smith D (2010) Cities feeding people: an update on urban agriculture in equatorial Africa. Environ Urban 22:483–499

Lu T, Brandt M, Tong X, Hiernaux P, Leroux L, Ndao B, Fensholt R (2022) Mapping the abundance of multipurpose agroforestry Faidherbia albida trees in Senegal. Remote Sens 14: 662. https://doi.org/10.3390/rs14030662

Lwasa S, Mugagga F, Wahab B, Simon D, Connors JP, Griffith C (2015) A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. Curr Opin Environ Sustain 13:68–73. https://doi.org/10.1016/j.cosust.2015.02.003

Manaye A, Tesfamaridm B, Tesfaye M, Worku A, Gufi Y (2021) Tree diversity and carbon stocks in agroforestry systems in northern ethiopia. Carbon Balance Manage 16(1):7. https://doi.org/10.1186/s13021-021-00174-7

Mansourian S, Berrahmouni N (2021) Review of forest and landscape restoration in Africa. FAO and AUDA-NEPAD, Accra

Marais ZE, Baker TP, O'Grady AP, England JR, Tinch D, Hunt MA (2019) A natural capital approach to agroforestry decision-making at the farm scale. Forests 10(11):980. https://doi.org/10.3390/f10110980

Marsden C, Martin-Chave A, Cortet J, Hedde M, Capowiez Y (2020) How agroforestry systems influence soil fauna and their functions - a review. Plant Soil 453:29–44

Mbow C, van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67

McNeely J, Schroth G (2006) Agroforestry and biodiversity conservation—traditional practices, present dynamics, and lessons for the future. Biodivers Conserv 15:549–554

Mehrabi Z, Ramankutty (2019) Synchronized failure of global crop production. Nat Ecol Evol 3: 780–786

Meybeck A, Gitz V (2017) Sustainable diets within sustainable food systems. Proc Nutr Soc 76:11

Mulia R, Hoang SV, Dinh VM, Duong NBT, Nguyen AD, Lam DH, Thi Hoang DT, van Noordwijk M (2021) Earthworm diversity, forest conversion and agroforestry in Quang Nam Province, Vietnam. Landscape 10:36. https://doi.org/10.3390/land10010036

Murdiyarso D, Van Noordwijk M, Wasrin UM, Tomich TP, Gillison AN (2002) Environmental benefits and sustainable land-use options in the Jambi transect, Sumatra, Indonesia. J Veg Sci 13:429–438

Nair PKR (1985) Classification of agroforestry systems. Agrofor Syst 3:97–128. https://doi.org/10.1007/BF00122638

Nair PKR (2012) Climate change mitigation: a low-hanging fruit of agroforestry. In: Nair PKR, Garrity DP (eds) Agroforestry: the future of global land use. Springer, New York, pp 31–67

Nair PK, Kumar BM, Nair VD (2021) An introduction to agroforestry: four decades of scientific developments. Springer, Cham

Nath A, Kumar R, Devi N, Rocky P, Uttam KG, Rai KS, Bajpai K, Sahu N, Pandey R (2021) Agroforestry land suitability analysis in the Eastern Indian Himalayan region. Environ Challenges. https://doi.org/10.1016/j.envc.2021.100199

Newmark WD, Jenkins CN, Pimm SL, McNeally PB, Halley JM (2017) Targeted habitat restoration can reduce extinction rates in fragmented forests. Proc Natl Acad Sci 114:9635–9640

Nguyen Q, Hoang MH, Oborn I, van Noordwijk M (2013) Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. Clim Chang 117(1):241–257

Niether W, Jacobi J, Blaser WJ, Andres C, Armengot L (2020) Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ Res Lett 15:53. https://doi.org/10.1088/1748-9326/abb053

Olsson L, Barbosa H, Bhadwal S, Cowie A, Delusca K, Flores-Renteria D, Hermans K, Jobbagy E, Kurz W, Li D, Sonwa DJ, Stringer L (2019) Land degradation. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva

Plieninger T, Muñoz-Rojas J, Buck LE et al (2020) Agroforestry for sustainable landscape management. Sustain Sci 15:1255–1266. https://doi.org/10.1007/s11625-020-00836-4

Prain G, Karanja N, Lee-Smith D (2010) African urban harvest: agriculture in the cities of Cameroon, Kenya and Uganda. Springer, New York

Pretty J (2018) Intensification for redesigned and sustainable agricultural systems. Science 362:362

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114: 1571–1596

Rahman PM, Varma RV, Sileshi GW (2012) Abundance and diversity of soil invertebrates in annual crops, agroforestry and forest ecosystems in the Nilgiri biosphere reserve of Western Ghats, India. Agrofor Syst 85:165–177

Rockström J, Williams J, Daily G et al (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46:4–17

Rosenstock TS, Dawson IK, Aynekulu E, Chomba S, Degrande A, Fornace K, Jamnadass R, Kimaro A, Kindt R, Lamanna C, Malesu M, Mausch K, McMullin S, Murage P, Namoi N, Njenga M, Nyoka I, Paez Valencia AM, Sola P, Shepherd K, Steward P (2019) A planetary health perspective on agroforestry in Sub-Saharan Africa. One Earth 1(3):330–344

Royal Society (2009) Reaping the benefits, science and the sustainable intensification of global agriculture. RS Policy document 11/09. Royal Society, London

Santos M, Cajaiba RL, Bastos R, Gonzalez D, Petrescu Bakis A-L, Ferreira D, Leote P, Barreto da Silva W, Cabral JA, Gonçalves B, Mosquera-Losada MR (2022) Why do agroforestry systems enhance biodiversity? Evidence from habitat amount hypothesis predictions. Front Ecol Evol 9: 630151. https://doi.org/10.3389/fevo.2021.630151

Schoeneberger MM, Bentrup G, Gooijer de H, Soolanayakamahally R, Sauer T, Brandle J, Zhou X, Current D (2012) Branching out: agroforestry as a climate change mitigation and adaptation for agriculture. J Soil Water Conserv 67:128–136

Science Task Force for the UN Decade on Ecosystem Restoration (2021) Science-based ecosystem restoration for the 2020s and beyond. IUCN, Gland, p 60

Sheppard JP, Bohn Reckziegel R, Borrass L, Chirwa PW, Cuaranhua CJ, Hassler SK, Hoffmeister S, Kestel F, Maier R, Mälicke M, Morhart C, Ndlovu NP, Veste M, Funk R, Lang F, Seifert T, du Toit B, Kahle H-P (2020) Agroforestry: an appropriate and sustainable response to a changing climate in Southern Africa? Sustain For 12(17):6796. https://doi.org/10.3390/su12176796

Shin S, Soe KT, Lee H, Kim H, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11(4):368. https://doi.org/10.3390/f11040368

Sileshi WG, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307:1–19

Sileshi WG, Mafongoya PL, Nath AJ (2020) Agroforestry systems for improving nutrient recycling and soil fertility on degraded lands. In: Dagar JC et al (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1. Springer, Singapore, pp 225–254. https://doi.org/10.1007/978-981-15-4136-0_8

Simkin RD et al (2022) Biodiversity impacts and conservation implications of urban land expansion projected to 2050. Proc Natl Acad Sci U S A 119:e2117297119

Syampungani S, Chirwa PW, Akinnifesi FK, Ajayi OC (2010) The potential of using agroforestry as a WinWin solution to climate change mitigation and adaptation and meeting food security challenges in Southern Africa. Agric J 5:80–88. https://doi.org/10.3923/aj.2010.80.88

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci U S A 108:20260–20264

Tollefson J (2021) IPCC climate report: earth is warmer than it's been in 125,000 years. Nature 596: 171–172

Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric Ecosyst Environ 230:150–161

Udawatta P, Rankoth RL, Jose S (2019) Agroforestry and biodiversity. Sustain For 11(10):2879. https://doi.org/10.3390/su11102879

Udawatta P, Rankoth RL, Jose S (2021) Agroforestry for biodiversity conservation. In: Udawatta RP, Jose S (eds) Agroforestry and ecosystem services. Springer, Cham, pp 245–274

United Nations (2015) Transforming our world: the 2030 agenda for sustainable development. General Assembly 70 session

United Nations (2019) Resolution adopted by the general assembly on 1 March 2019. https://undocs.org/A/RES/73/284. Accessed 31 Oct 2021

Valderrábano M, Nelson C, Nicholson E, Etter A, Carwardine J, Hallett JG, McBreen J, Botts E (2021) Using ecosystem risk assessment science in ecosystem restoration: a guide to applying the Red List of Ecosystems to ecosystem restoration. IUCN, Gland

Van Noordwijk M, Duguma LA, Dewi S, Leimona B, Catacutan DC, Lusiana B, Öborn I, Hairiah K, Minang PA (2018) SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? Curr Opin Environ Sustain 34:33–42. https://doi.org/10.1016/j.cosust.2018.09.003

Van Noordwijk M, Coe R, Sinclair FL, Luedeling E, Bayala J, Muthuri CW, Cooper P, Kindt R, Duguma L, Lamanna C, Minang PA (2021) Climate change adaptation in and through agroforestry: four decades of research initiated by Peter Huxley. Mitig Adapt Strateg Glob Chang 26: 18. https://doi.org/10.1007/s11027-021-09954-5

Verchot LV, Noordwijk MV, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strateg Glob Chang 12:901–918

Verchot L, De Sy V, Romijn E, Herold M, Coppus R (2018) Forest restoration: getting serious about the 'plus' in REDD+. 2018. Introduction: REDD+enters its second decade. In: Angelsen A, Martius C, De Sy V, Duchelle AE, Larson AM, Pham TT (eds) Transforming REDD+: lessons and new directions. CIFOR, Bogor, pp 189–202

Waldron A, Garrity D, Malhi Y, Girardin C, Miller DC, Seddon N (2017) Agroforestry can enhance food security while meeting other sustainable development goals. Trop Conserv Sci. https://doi.org/10.1177/1940082917720667

Wezel A, Herren BG, Kerr RB, Barrios E, Gonçalves AR, Sinclair F (2020) Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron Sustain Dev 40:40

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk A, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6:1–12. https://doi.org/10.1038/srep29987

Chapter 2
Agroforestry Matches the Evolving Climate Change Mitigation and Adaptation Agenda in Asia and Africa

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Abstract Mitigadaptation, tree-based synergy between the global climate change mitigation and adaptation agendas, has been slowly emerging in the 30 years of climate science–policy interaction with its various ups and downs, false starts and ever-increasing urgency of bending the climate curve. The potential contribution of agroforestry to the climate change mitigation and adaptation agenda has been slow to

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be recognized and effectively supported, as agroforestry existed on farm and in landscapes, but not yet in the world of policy documents, government statistics and sectoral lobby groups. The articulation of the 17 sustainable development goals that transcend sectoral claims for prioritization and call for results-oriented investment of public funds has made it easier for the adaptation and mitigation agendas to synergize. Especially where focus is on local livelihoods in green economies, creating space for a continuum approach to Agriculture, Forestry and Other Land Uses (AFOLU), within which trees outside forest and agroforestry can be recognized for what they are. The chapter takes stock of such changes, as they played out in Africa and Asia, especially, by reviewing three agroforestry concepts. The third, policy-oriented, agroforestry concept (AF3) deals with the existing forestry-agriculture dichotomy and creates space for a landscape land-use continuum, with results-based management, clarifying institutional versus vegetation-based forest concepts. The second, landscape-oriented, agroforestry concept (AF2) emphasizes multifunctionality of managing land and water for the full set of SDGs and awareness of natural and man-made disasters, supporting collective action and active participation in value chains. The first, farm-oriented, agroforestry concept (AF1) has its roots in risk management through diversity and is the primary level for climate change adaptation and climate-smart solutions. The concepts jointly interact with data, feedbacks, institutions and goals as part of complex, adaptive social-ecological systems.

Keywords Agroforestry concepts · Leverage points · Mitigadaptation · Sustainable development goals

2.1 Introduction

Forests of all types, biodiversity and sustainable land use are, according to World leaders (Box 2.1), expected to save people from the threat of global climate change and help us achieve the Sustainable Development Goals (SDGs). With this level of recognition of the relevance of tree cover and commitment to overcome constraints, there shouldn't be difficulties to ensure that agroforestry, a form of sustainable land use and, depending on definitions used, a type of forest, is used to its potential. Yet, there remains some work to be done. The day after the Glasgow declaration, the Indonesian Minister of Environment and Forestry warned that, although the president had signed the declaration, the country could not guarantee that its goals would be achieved—at least not without further discussion, means of implementation and details in which the devil may hide. In this chapter, we will review how agroforestry answers are part of the evolving climate change mitigation and adaptation agenda in Asia and Africa.

Box 2.1 Glasgow Leaders' Declaration on Forests and Land Use[1]—November 2021 [Our Underlining]

We, the leaders of the countries identified below:

Emphasise the critical and interdependent roles of forests of all types, biodiversity and sustainable land use in enabling the world to meet its sustainable development goals; to help achieve a balance between anthropogenic greenhouse gas emissions and removal by sinks; to adapt to climate change; and to maintain other ecosystem services.

Reaffirm our respective commitments, collective and individual, to the UN Framework Convention on Climate Change and the Paris Agreement, the Convention on Biological Diversity, the UN Convention to Combat Desertification, the Sustainable Development Goals; and other relevant initiatives.

Reaffirm our respective commitments to sustainable land use, and to the conservation, protection, sustainable management and restoration of forests, and other terrestrial ecosystems.

Recognise that to meet our land use, climate, biodiversity and sustainable development goals, both globally and nationally, will require transformative further action in the interconnected areas of sustainable production and consumption; infrastructure development; trade; finance and investment; and support for smallholders, Indigenous Peoples, and local communities, who depend on forests for their livelihoods and have a key role in their stewardship.

Highlight the areas of strong progress in recent years and the opportunities before us to accelerate action.

We therefore commit to working collectively to halt and reverse forest loss and land degradation by 2030 while delivering sustainable development and promoting an inclusive rural transformation.

We will strengthen our shared efforts to:

1. Conserve forests and other terrestrial ecosystems and accelerate their restoration;
2. Facilitate trade and development policies, internationally and domestically, that promote sustainable development, and sustainable commodity production and consumption, that work to countries' mutual benefit, and that do not drive deforestation and land degradation;
3. Reduce vulnerability, build resilience and enhance rural livelihoods, including through empowering communities, the development of profitable, sustainable agriculture, and recognition of the multiple values of forests, while recognising the rights of Indigenous Peoples, as well as local communities, in accordance with relevant national legislation and international instruments, as appropriate;

(continued)

[1] https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/.

Box 2.1 (continued)

4. Implement and, if necessary, redesign agricultural policies and programmes to incentivise sustainable agriculture, promote food security, and benefit the environment;
5. Reaffirm international financial commitments and significantly increase finance and investment from a wide variety of public and private sources, while also improving its effectiveness and accessibility, to enable sustainable agriculture, sustainable forest management, forest conservation and restoration, and support for Indigenous Peoples and local communities;
6. Facilitate the alignment of financial flows with international goals to reverse forest loss and degradation, while ensuring robust policies and systems are in place to accelerate the transition to an economy that is resilient and advances forest, sustainable land use, biodiversity and climate goals.

We urge all leaders to join forces in a sustainable land use transition. This is essential to meeting the Paris Agreement goals, including reducing vulnerability to the impacts of climate change and holding the increase in the global average temperature to well below 2 °C and pursuing efforts to limit it to 1.5 °C, noting that the science shows further acceleration of efforts is needed if we are to collectively keep 1.5 °C within reach. Together we can succeed in fighting climate change, delivering resilient and inclusive growth, and halting and reversing forest loss and land degradation.

From its early days as an emerging science, agroforestry research has considered the relationship between climate and trees as a two-way interaction (van Noordwijk et al. 2021): not only do climatic characteristics determine which trees can grow where, as is commonly studied for any crop, but trees also modify the (micro)climate in their neighbourhood, and modify the climate in which crops grow, and livestock graze and seek shelter. Major advances in the understanding of this two-way interaction have been made as part of the early 'Diagnose and Design' efforts to match local agroforestry ambitions to realities of landscapes, markets and climates (Mbow et al. 2014a; van Noordwijk et al. 2016a, b), but also at the ecophysiological level (van Noordwijk et al. 2014c; Ong et al. 2015; Bayala et al. 2015). The flexibility and *sustainagility* (resource base for continued innovation) of agroforestry is particularly relevant when facing uncertainty about weather patterns and future climate trajectories (Verchot et al. 2007). It led to the coining of the term '*mitigadaptation*' (van Noordwijk et al. 2011; Prasad et al. 2014), as trees and people can, within limits, co-adapt to the conditions that result from the recycling of fossil fuels to the atmosphere, and via that to oceans and terrestrial systems: the *mitigation* agenda (reducing the atmospheric loading with greenhouse gases) can be addressed in parallel with the *adaptation* agenda (reducing the negative consequences of the resulting global climate change) (Cardinael et al. 2021).

2.2 A Meadows-Based Hierarchy in Theories of Change

The most challenging aspect for successful transformations towards sustainability (including climate change mitigation + adaptation) is to reconcile two hierarchies (Fig. 2.1): (a) individuals nested in households nested in communities nested in subnational jurisdictions nested in nation states part of global humanity, and (b) a Meadows (1999)-based hierarchy of levels of 'leverage' on complex, adaptive social-ecological systems: data, feedbacks, institutions and goals as they are related in 'issue attention cycles' of policy change (van Noordwijk 2018). Across these two classifications, a wide range of aspects relate agroforestry to climate change (Fig. 2.1):

1. Data collection connects individuals to global scales, deals with challenges to 'representativeness' (or bias), double-counting and gaps at the various scale transitions, temporal variation, time-lags, 'slow variables' and thresholds in non-linear patterns of change.
2. Functional feedbacks are the basis of 'system dynamic' models that can be used for scenario studies to identify 'theories of change' that lead to desirable or undesirable outcome.

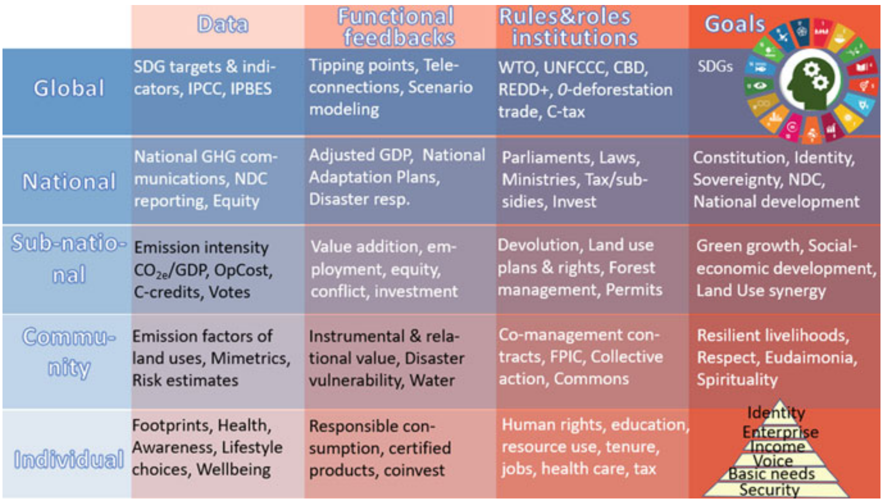

Fig. 2.1 Meadows (1999)-based hierarchy (data, feedbacks, institutions, goals) across individual-to-global scales with examples of specific concerns in understanding and nudging societies; CBD = convention on biological diversity; FPIC = free and prior informed consent; GDP = gross domestic product; IPBES = intergovernment science-policy panel on biodiversity and ecosystem services; IPCC = Intergovernment Panel on Climate Change; NDC = Nationally Determined Contribution; OpCost = opportunity costs; REDD+ = reducing emissions from deforestation and (forest) degradation; UNFCCC = UN Framework Convention on Combatting Climate Change; WTO = World Trade Organization (reproduced with permission from van Noordwijk et al. 2020b)

3. The roles and rules articulated in institutions operate at the interface of fairness and efficiency, connecting local to global scales and vice versa.
4. Goals, as top of the leverage pyramid at each scale, can have friction across scales where the sum of goals at a constituent level does not match the way goals are articulated and operationalized (in institutions) one scale up.

To analyse the complementarity and possible synergy between plot/farm, landscape and policy-level agroforestry concepts (labelled here as AF1, AF2 and AF3, respectively; van Noordwijk et al. 2016a, 2018) in the interaction of patterns (data), processes (feedbacks), institutions and goals, we may have to start at the policy level. Leveraging at these different scales and contexts requires understanding the weak points in the whole complex of scales and contexts. Usually, the highest leveraging potential ('theory of induced change') arises from the elements of the system that connect to adjacent feedback loops and institutional structures.

2.3 AF3: Synergistic Policy Approaches

2.3.1 Sustainable Development Goals (SDGs) as Holistic Framing

Of the three UN conventions adopted in 1992 in Rio, the 'desertification' convention UN-CCD has faced the most challenges to move beyond 'honourable intentions', until the global agenda on Forest and Landscape Restoration (FLR) took centre stage. The restoration agenda links the two main parts of the UNFCCC, the climate change mitigation (CC*Mit*) and the climate change adaptation (CC*Adapt*) action programmes, and blends it with ambitions of the biodiversity convention (CBD). The mix is attractive to policy makers, but also confusing as it involves many trade-offs without clarity on how to weigh the various goals. The third, policy-oriented, agroforestry concept (AF3), however, is at the centre of this debate (Fig. 2.2). Effective action to meet SDG targets needs recognition of trade-offs at the feedback and institution (rather than only data) level, finding ways to ensure all goals are understood to be compatible and relevant by all. Potential synergistic opportunities may be easily overshadowed by the trade-offs. An evidence, data-based approach, reconciled with up-to-date science on feedbacks and political understanding of institutional roles can help identify strategies to manage the unavoidable trade-offs in local context. Continuous monitoring and assessment of emergent system elements and properties that increase synergies and or trade-offs should also be part of the discourse in the planning processes, as data can be safely interpolated, but applicability may change when global systems enter new territories.

Fig. 2.2 The third, governance and policy-level agroforestry concept (AF3) is positioned in a world shaped by Sustainable Development Goals and is at the interface of the three Rio conventions UNFCCC, CBD and UNCCD)

2.3.2 Agroforestry and Climate Mitigation Challenges at the Interface of Trade and Nation-States

Agroforestry is a subcomponent of the global C cycle and its representation in the governance systems that either focus on national boundaries (AFOLU accounting, NDC, Green Growth) or consumer responsibility and corporate image (Fig. 2.3). A remarkable shift occurred between the 2000 IPCC assessment of agroforestry as part of mitigation options in global land use (Watson et al. 2000) and the 2014 (Smith et al. 2014) study of mitigation options within the agriculture, forestry and other land use (AFOLU) continuum; the latter study ranked agroforestry as promising approach when multiple goals and functions (beyond mitigation per se) are considered. Agroforestry is a prominent part of discussions on ecosystem-based adaptation for smallholder farmers (Vignola et al. 2015).

As explored by Duguma et al. (2014a, b), the main obstacles to benefitting from the synergy between mitigation and adaptation are part of the path dependency of the global climate discourse: the opportunities for adaptation were, in the first decade

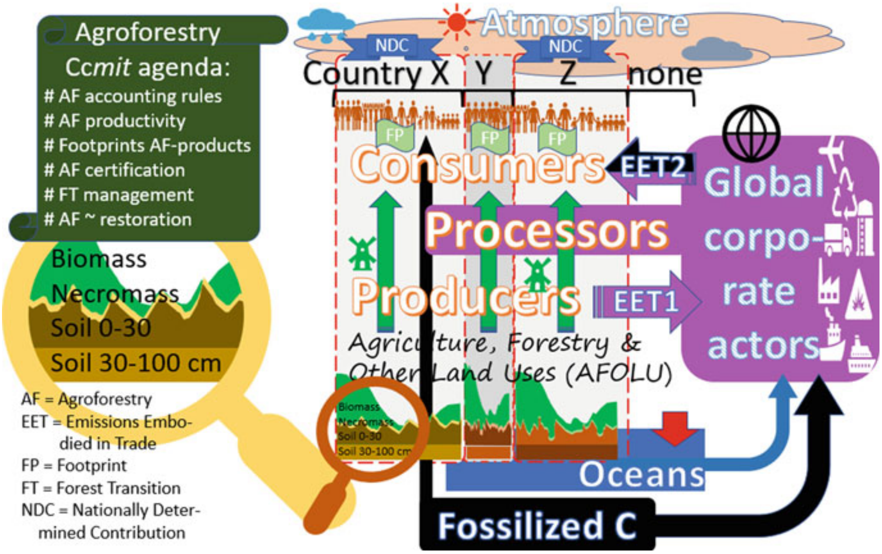

Fig. 2.3 Agroforestry as a subcomponent of the global C cycle and its representation in the governance systems that either focus on national boundaries (AFOLU accounting, NDC, Green Growth) or consumer responsibility and corporate image (zero-deforestation, C-neutrality, C-positivity); (reproduced with permission from van Noordwijk et al. 2020b)

after the 1992 UN Framework Convention on Combatting Climate Change (UNFCCC), seen to undermine the urgency of climate change mitigation. Subsequently, three requirements for mitigation-related project funding have been hard to meet: (1) 'additionality', showing that emission-reducing activities would not have occurred based on current market conditions, (2) 'permanence' expecting that emission reduction keeps a specified amount of greenhouse gasses out of the atmosphere without further investment and (3) 'leakage' avoiding a shift of emission-causing activities to areas outside of the project boundary (van Oosterzee et al. 2012; Thamo and Pannell 2016). An earlier review (Lasco et al. 2014a, b) found that national policies remain incoherent and need to be more explicit if local action is to be supported and benefits realized. There has been progress in a number of countries, at least, but challenges remain.

Agroforestry is currently a small part of the complex network of relations around global mitigation of climate change via the 'emission transition' from a phase of net anthropogenic emissions of greenhouse gasses, to one of net absorption by oceans and land surfaces. To understand this complexity, the roles of nation-states, corporate actors (operating across nations) and consumers need to be related to the aspirations (goals) articulated, the accounting rules that have emerged, and the gaps between ambitions and practice as reflected in the data available. The initiative for dealing with the threat of global climate change was since 1992 with the conference of parties to the UNFCCC. However, despite ambitious goals about limits to acceptable global warming, and articulations of 'common but differentiated responsibility' (CBDR; van Noordwijk and Catacutan 2017), progress has been, among others, limited by:

1. The dichotomy between Annex-I and non-Annex-I countries in the roles they were expected to play, despite the considerable diversity in each group, coupled to low levels of trust within and among these groups, and multiple ways CBDR could be understood,
2. Underestimating the interface between fossil fuel-based emissions (the target for direct action) and land cover/land use issues, leading to the attention on pseudo-solution of biofuels where emissions caused in land clearing and production remained outside of the accounting rules,
3. The accounting rules for Agriculture, Forestry and Other Land Uses (AFOLU) that were meant to be comprehensive (no cracks between sectors, no double-counting), but lead to blind spots for TOF trees ('trees on farm', or 'trees outside forest'; Zomer et al. 2016; Rosenstock et al. 2019a; Skole et al. 2021) and challenges in accounting for agricultural use of formerly forested wetlands (van Noordwijk et al. 2014b),
4. Challenges on how to represent carbon-rich products of land use with contested necromass half-life times in the account, an issue strongly pushed by countries with a tradition of exporting wood-products, but not deemed applicable to 'agricultural' products,
5. Confusion between 'institutional' and 'vegetation-based' interpretation of forests that hindered application of the A/R-CDM (Afforestation and Reforestation forms of the Clean Development Mechanism; van Noordwijk et al. 2008),
6. Refusal by forest authorities and forest-governance bodies to distinguish between 'natural forest' and 'plantations', contrary to demands by climate activists, with a complete absence of an intermediate 'agroforest' category on either side of this debate,
7. Fear that the 'avoided emissions' represented by protecting existing carbon stocks in forests and peatlands would be too easy and cheap, and slow down the required energy transition,
8. Underestimating the social complexity of achieving meaningful changes in the shifts of tropical forest margins, due to conflicting claims between nation states and indigenous people with long histories in the forest area (van Noordwijk et al. 2014a), as well as the trade-offs between development ambitions of local/national governments and global concerns over land-based emissions,
9. Opportunities for Annex-I countries to meet their international obligations by not only 'outsourcing' emission-intensive heavy industry to non-Annex-I countries, but also protecting their domestic forests while increasing their external footprint for agricultural and forestry products—as clarified in the Emissions Embodied in Trade (EET) literature (Minang et al. 2010; Henders et al. 2015; Pendrill et al. 2019),
10. Procedural rules mean to maintain a clear budgetary separation between 'climate finance' and 'development support' on one hand, and between climate change 'mitigation' and 'adaptation', on the other.

Nationally Determined Contributions (NDCs) have emerged as the main tool for defining, communicating and potentially reporting party contributions to the Paris Agreement on climate change. Agroforestry has been identified as a key part of most developing country NDCs, hence it is a potentially important contributor to global climate objectives (Duguma et al. 2022). By converting 25% of deforested areas to agroforestry, about 80% of the non-annex-I countries could achieve their unconditional commitments. The widespread use of agroforestry (about one billion hectares) and the familiarity of smallholder farmers and local practitioners make it a potential low-hanging fruit for achieving NDCs commitments, emission reduction in agriculture and resilience. However, there are financial, policy and technology challenges that should be addressed including land and tree tenure and carbon rights in some countries, potential impacts of climate change on the growing niches of tree species, and limited sources of quality germplasm.

2.3.3 Consumer, Citizen and Private Sector Responsiveness Pushing National Agendas

Global anthropogenic greenhouse gas emissions can be attributed to human activity in multiple ways, including: based on the land and sea areas countries control, based on the economic activity that generates them or based on the people who drive the economy (Table 2.1). Policy coherence must be achieved at a number of levels, from international to local, to avoid conflicting rules and incentives (Carter et al. 2018).

As nation-states collectively failed to resolve such issues in a timely fashion, and citizen concern over the urgency of the issues kept increasing, an alternative arena for action became the personal responsibility for 'footprint' consequences of consumption and life-style choices, initially especially in the Global North and driven by young people, the (threats of) boycotts of products that were singled out in public

Table 2.1 Three ways global anthropogenic emissions can be accounted for and governed

	Nation states	Private (corporate) sector	Consumers, citizens
Accounting target	Net emissions within national boundaries; pledged and supported NDC	Emission intensity (attributable emissions per unit economic turnover)	Per capita emissions; individual footprints (domestic + global)
Gaps	Emissions embodied in trade; international waters; biofuel-based emissions	Sea and air transport; responsibility for 'indirect land-use change'	Life cycle Accounting beyond consumable products
Interfaces	Carbon markets created by tradeable emission rights for corporates; carbon tax at international borders		Response to changing prices for goods and services
	Fear of loss of sovereignty, national standards to regain trust and maintain exports	Consumer pressure to obtain 'cheap but green' products; sector-level standards, commitments, certification	

communication (such as palm oil), and the responses of part of the global corporate sector, keen to protect their branding and public image. The result has been an avalanche of declarations, commitments and stated ambition to become deforestation-free, carbon-neutral, carbon-positive and so on. Where nation-states become the primary agents in UN-based discussions, the route to change via global citizens, consumer power and a responsive corporate sector (that want to be seen as responsible) remains a separate track with challenging 'market-based' interfaces with Nationally Determined Contributions (NDCs) of the countries in which goods are produced, consumers reside and/or companies have their legal basis (Box 2.2).

Box 2.2 Paris Rule Book

The recent COP26 of the UNFCCC in 2021 agreed on an operational set of rules for the Paris Agreement[2] of 2015, in its Article 6:

1. "Parties recognize that some Parties choose to pursue voluntary cooperation in the implementation of their nationally determined contributions to allow for higher ambition in their mitigation and adaptation actions and to promote sustainable development and environmental integrity.
2. Parties shall, where engaging on a voluntary basis in cooperative approaches that involve the use of internationally transferred mitigation outcomes towards nationally determined contributions, promote sustainable development and ensure environmental integrity and transparency, including in governance, and shall apply robust accounting to ensure, inter alia, the avoidance of double counting, consistent with guidance adopted by the Conference of the Parties serving as the meeting of the Parties to this Agreement."

The 'rulebook' had taken so long, as it involves the transparency and reporting requirements for all Parties to track progress against their emission reduction targets.[3,4] The Rulebook sets out the functioning of international carbon markets to support further global cooperation on emission reductions. However, the focus remains on Government-to-Government rules for how countries can deduct emissions reduced outside their borders from emissions occurring within their borders, only if the host country agrees not to report these as part of their 'Nationally Determined Contributions' (NDCs). There still are complex questions about the interface of corporate sector commitments to global citizens and consumers to achieve 'carbon-neutrality' through investments in 'offsets', and the way the countries where activities occur and

(continued)

[2] https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[3] https://www.adb.org/sites/default/files/publication/664051/article6-paris-agreement-v2.pdf.

[4] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6021.

Box 2.2 (continued)
where consumers live or corporations are registered, report their emissions. Carbon markets can only operate within clear rules, and so far these markets will remain segmented by the different rules that operate within e.g. the European Union, and across its external borders. Meanwhile, the corporate sector can try to build trust in its 'brands' through its own public commitments—without standardized reporting requirements, and well-intentioned global citizens try to minimize their 'footprints', without clarity on how this contributes to NDCs.

2.3.4 From REDD+ to Reducing Emissions from All Land Uses

The central offer of REDD+ consists of results-based payments to forest-rich countries for protecting forests and avoiding carbon emissions (Martius and Duchelle 2021). The challenges associated with this approach are large, as there are powerful interests (such as unsustainable timber extraction, conversion to agricultural land, mining or land speculation) in maintaining the status quo of unsustainable deforestation and forest degradation (De Sy et al. 2018) and the challenge in setting up an accountable benefit-sharing mechanism (Hoang et al. 2013; Wong et al. 2019; Pham et al. 2021). Halting forest loss and achieving sustainable development also requires tackling deeply established patterns of inequality and power relations embedded in forest and agricultural land use (Brockhaus et al. 2021; Larson et al. 2021), strong political leadership, and a transformative coalition for changes (Korhonen-Kurki et al. 2019). Unless REDD+ funds are used to bend the forest transition curve by providing alternative non-forest-based employment, plus increasing domestic demand for and political pressure to maintain the benefits intact forests provide, it may delay but not avoid emissions. From the early days of REDD+, the question has been whether it leads to a new mode of governance or remains 'just another project' (Moeliono et al. 2020).

Lessons learned from experience on the ground with the highly diverse bundles of REDD+ interventions (Duchelle et al. 2018) were that there has been insufficient use of counterfactuals to attribute outcomes to REDD+, that the non-carbon effects were generally small or insignificant and that relatively few studies focused on the carbon outcomes of REDD+. The national forest monitoring systems in most countries do not link to comprehensive data on direct drivers and agents driving forest change, to basic socioeconomic and other data on underlying causes of forest change (De Sy et al. 2018). Researchers concluded that local participation in REDD+ needs a boost to help achieve positive outcomes. 'For REDD+ to be effective, forest-based mitigation needs to be incorporated in national development and climate action plans, and mainstreamed across sectors and levels of government. A strong positive narrative on how forests contribute to economic development and climate goals can support this integration' (Angelsen et al. 2018)—the latter might be easier if the forest concepts promoted more explicitly include agroforestry and trees outside forest, as was proposed in the Reducing Emissions from All Land Uses (REALU) attempt that failed to get traction in the negotiations (Mertz et al. 2012; Bernard et al. 2013; Minang and van Noordwijk 2014; Vanderhaegen et al. 2015). Government motivation to engage with REDD+ discussions and experiments included concerns over the country's securities (food, water, shelter, coastal integrity) facing climate change, the expectation of fungible income sources and the protection of the national 'brand' and role as exporter of responsibly produced commodities (van Noordwijk et al. 2014a). Promoting agroforestry is included in a large number of REDD+ and restoration programmes and projects in Africa and Latin America (Verchot et al. 2018), but as a 'means' of achieving forest-centric goals.

Agroforestry can contribute to the success (supporting livelihoods while protecting carbon stocks) of REDD+ landscapes in multiple ways (Minang et al. 2014): (1) Agroforests as C-rich land use practice at risk of simplification and replacement by land uses (e.g. rotations of fast-growing trees) as direct target of deflecting pressures, (2) Agroforestry as strategic option to address drivers of deforestation by providing income and sustainably produced forest products and (3) Agroforestry as option for the social plus ecological aspects of forest and landscape restoration. However, higher yields with agroforestry practices may provide incentives to expand agricultural land use into remaining forests, so policies need to incorporate forest-specific measures to ensure land-sparing outcomes (Tomich et al. 1998; Ngoma et al. 2018).

2.3.5 Policy-Level Recognition for Agroforestry

A comprehensive review for southern Africa (Sheppard et al. 2020) supported agroforestry systems as an appropriate and sustainable response for an increased resilience against a changing climate for the benefit of livelihoods and multiple environmental values, but identified deficiencies in the institutional and policy frameworks that underlie the adoption and stimulus of agroforestry in the region.

The 40th conference of ASEAN (Association of Southeast Asian Nations) Ministers on Agriculture and Forestry in October 2018 adopted the *ASEAN Guidelines for Agroforestry Development*. A recent report (Box 2.3) commissioned by the FAO under a Technical Cooperation Programme with ASEAN reviewed the scaling up of agroforestry for livelihoods and environmental benefits in ASEAN (Lin et al. 2021). Since agroforestry is not yet included in national reporting by either the forestry or agricultural sectors, the report relied on primary analyses drawn from the literature, contributions from agroforestry researchers and expert practitioners, and survey data gathered from delegates to the ASEAN Working Group on Social Forestry.

Box 2.3 ASEAN Embracing Agroforestry

A stocktake (Lin et al. 2021) of agroforestry in ASEAN (Association of Southeast Asian Nations) concluded:

- Agroforestry is expanding in Southeast Asia. Over the last decade, trees outside forests have increased three times more than trees inside forests across the Mekong Region, indicating a reversal in deforestation. These gains mostly occurred on croplands, grasslands and settlements. Despite this increase, agroforestry is missing in national accounting systems. A land-use classification and operational definition of agroforestry are necessary to monitor changes.
- Without an institutional home, agroforestry will remain at the periphery of the agri-food, forest and land-use sectors. National policies and programming for agroforestry will help clarify overlapping and conflicting land-use policies and provide social protection to smallholders and community forest users engaged in tree-based systems and related practices in and outside forests.
- A regional analysis of agroforestry practices shows similarities in approaches across Southeast Asia, highlighting the wider adaptability of these practices and the utility of establishing a regional knowledge management system to extract and build on lessons learned.
- The costs of environmental disasters in the region between 2000 and 2020 were more than USD 122 trillion, affecting over 324 million people. Growing trees can stabilize food supplies and incomes through diversification and provide physical protection against extreme weather events. Smallholders are increasingly adopting agroforestry to mitigate, and adapt to, climate change.
- Increased recognition of agroforestry's role in addressing climate change, food insecurity and land degradation, as well as the shift toward sustainable business models and community forestry schemes, has contributed to an increasing demand for agroforestry experts. However, agroforestry education programmes in the region remain scarce. Building on the progress of regional and national agroforestry education networks can accelerate progress toward meeting this demand.
- Limited incentives and financing mechanisms currently exist for agroforestry. Technical and resource support is critical, given that benefits from agroforestry accrue progressively over time. Emphasis needs to be placed on commodity value chains. Policymakers and practitioners should promote agroforestry in third-party certification programmes to increase smallholders' access to stable markets.
- The underlying framework for advancing agroforestry development already exists in most countries. The presence of an agroforestry agency,

(continued)

Box 2.3 (continued)

the development of agroforestry roadmaps, programmes and the availability of financing mechanisms can be used as indicators to measure the progress of agroforestry development in ASEAN.

In Peru agroforestry, concession schemes were introduced to formalize agriculture and timber production on forest lands as a means of reducing deforestation and forest degradation, and the country also adopted a comprehensive definition of agroforestry in its National Agricultural Policy. In Indonesia, similar policies are currently considered to deal with the 15–20% of oil palms that grow, without legal basis, in what is supposed to be the permanent forest estate (Purwanto et al. 2020).

2.4 AF2: Landscape-Level Livelihoods, Vulnerability and CC Adaptation

2.4.1 Human Vulnerability to Climate-Related Disasters

A significant part of climate change adaptation deals with managing human vulnerability to water-related 'disasters', where the distinction between 'natural' and 'man-made' has lost its meaning. Landslides, floods are triggered by intense rainfall, droughts and fires are caused by long dry periods where the meaning of 'extreme' and 'normal' is shifting due to climate change. Vulnerability is linked to being at the wrong time at the wrong place—but poverty often restricts the options of where to live.

Van Noordwijk et al. (2020b) summarized a Drivers-Pressures-State-Impacts-Responses analysis across seven 'degradation syndromes' and their agroforestry solutions: Degraded hillslopes, Fire-climax grasslands, Over-intensified monocropping, Forest classification conflicts, Drained peatlands, Converted mangroves and Disturbed soil profiles. Overarching concerns are a disturbed hydrology (van Noordwijk et al. 2020c, 2022a; Fig. 2.4) and, from an economic point of view, supply-sheds at risk. A range of metrics can be used in the diagnosis of agroforestry impacts in water cycles in relation to climate change risks (van Noordwijk et al. 2016b, 2022a, b).

2.4.2 Migration as a Choice

Human migration connects land use in areas of origin with areas of new residence, impacting both through individual, gendered choices on the use of land, labour and knowledge (Mulyoutami et al. 2020). Process-level understanding can be based on:

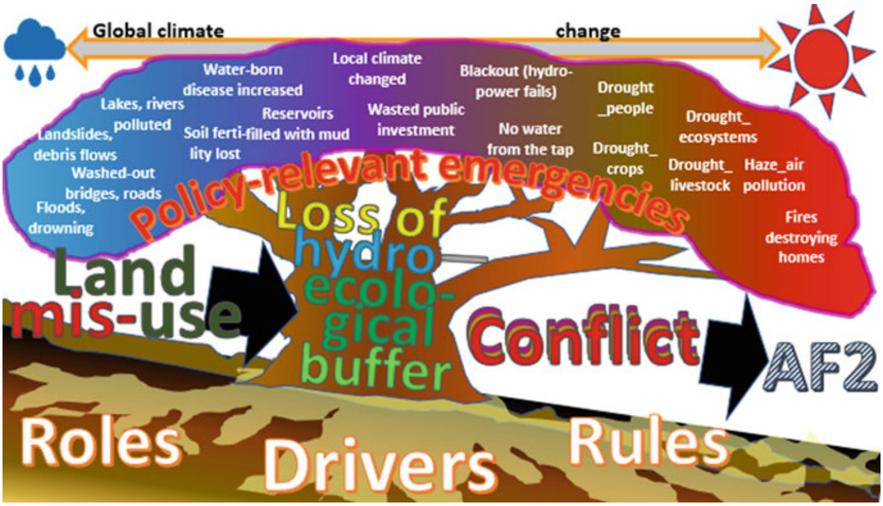

Fig. 2.4 The second, landscape and livelihoods-level agroforestry concept (AF2) deals with the drivers, pressures, system-state and impacts at landscape scale of land use interacting with climate change in causing and and/or avoiding disasters through institutions (rules and roles) (modified from van Noordwijk et al. 2020c)

(1) conditions within the community of origin linked to the reason for people to venture elsewhere, temporarily or permanently; (2) the changes in the receiving community and its environment, generally in rural areas with lower human population density; (3) the effect of migration on land use and livelihoods in the areas of origin; (4) the dynamics of migrants returning with different levels of success and (5) interactions of migrants in all four aspects with government and other stakeholders of development policies.

2.4.3 Segregated Versus Integrated Landscape Patterns as Basis of Multifunctionality

The discussion on how to achieve multiple functions compares 'sparing' and 'sharing' options, based on segregating or 'integrating' trees (van Noordwijk et al. 2012b; Minang et al. 2021b). Repackaged as 'land sparing' concept, the agricultural intensification ('Borlaug') hypothesis, that research on tropical forest margins had contested, came back in a new coalition of conservation agencies (who hoped it would be true) and agricultural scientists (who tried to make it work). Land sharing, as a counterpoint to land sparing, to promote multifunctional landscapes, was conceptually attractive to supporters of indigenous and local community rights and those promoting agroforestry as a solution, but was equally at risk of overgeneralizing evidence. In the interaction between plot, farm, landscape, national and global scales, both land sparing and land sharing sides of the argument had some relevant evidence to point at, but as a third side of the coin, the caring for each of the functions was identified as missing link.

Tree-crop expansion (cacao, oil palm) in a smallholder-dominated mosaic landscape in Ghana was linked to spatial segregation with adverse effects on food availability and ecosystem services (Asubonteng et al. 2020), with landscape structural properties similar to industrial agrarian landscapes with large segregated homogenous cocoa and oil palm areas, and a reserved forest area. Opportunities for functional integration apparently need further understanding of the driving forces of the current patterns. The Participatory Forestry Project (PFP) of the government of Sri Lanka promoted co-management of forests and household-level agroforestry to reduce deforestation and improve household livelihoods included woodlots, home garden development, and a village reforestation system for benefit sharing from agroforestry (De Zoysa and Inoue 2014). Various agroforestry options exist for bioenergy (Sharma et al. 2016). Traditional agroforestry practices in the hot Thar desert region of Rajasthan (India) having widely scattered trees/shrubs of various species in association with crops of food grain and fodder (Tewari et al. 2014) support remarkably high human population densities. Despite clear benefits as a time-proven sustainable land use system balancing food and fuelwood supply and fitting within available water resources, agroforestry systems in the Sahel still face challenges such as vague land use rights, inadequate capacities at farmer and government level, and lack of investments (Elagib and Al-Saidi 2020)

Varied ecological and socio-economic conditions have given rise to specific forms of agroforestry in different parts of Africa. Policies that institutionally segregate forest from agriculture miss opportunities for synergy at landscape scale. More explicit inclusion of agroforestry and the integration of agriculture and forestry agendas in global initiatives on climate change adaptation and mitigation can increase their effectiveness (Mbow et al. 2014b). Agroforestry requires several enabling conditions beyond biophysical suitability. For instance, the spread of Farmer-Managed Natural Regeneration (FMNR) of trees on croplands to 7 Mha in Niger (and about 21 Mha across the Sahelian countries) was triggered by a change in policy and development of markets for tree products (Garrity and Bayala 2019; Koffi and Worms 2021).

Failure of some agroforestry strategies is related to lack of integration and system approach (Mbow et al. 2014c). Key areas of critical lessons and contributions to practice and success of the past decades include incentives in landscapes (van Noordwijk et al. 2012a; Namirembe et al. 2017), landscape democracy (operationalization of democratic and good-governance principles such as participation and voice, strategic direction, accountability, transparency and fairness in multi-stakeholder processes at the landscape level; McCall and Minang 2005; Minang et al. 2015), the business case for landscape approaches (including private sector engagement), managing trade-offs and synergies, project co-location and portfolio management, and metrics, monitoring and learning (Minang et al. 2021a, b).

2.4.4 Functional Tree Diversity in Agroforestry

Recent collections of case studies on agroforestry as part of climate-smart land use with attention to both local and global ecosystem services beyond productivity (Castro et al. 2019; van Noordwijk 2021; Raj et al. 2020; Cardinael et al. 2021) provide context-specific detail, behind the general patterns discussed here. A study in Cameroon (Nyong et al. 2020) found that agroforestry practices especially home gardens with animals, home gardens, trees on grazing lands and coffee-based agroforestry played a significant positive role in enhancing smallholder farmers' resilience to the impacts of climate variability and change. Agroforestry benefits are often based on spreading of risks at portfolio level, increasing resilience as quantified for a site in Tanzania by Charles et al. (2013). Tree diversity is an important part of this (Ordonez et al. 2014). Opinions on the relevance of tree diversity for mitigation are mixed. On one hand, studies such as those of Tschora and Cherubini (2020) in Togo documented synergies between rural development and climate change adaptation benefits, but no clear relationship between biodiversity and carbon storage; they found a trade-off between high carbon stocks and crop yields across a range of agroforestry practices. This trade-off can be minimized with an optimal management of agroforestry by using a mix of tree species that store medium carbon stocks and can enhance yields, soil fertility and climate resilience. On the other hand, studies of biomass accumulation in variable climates often find an initial increase of biomass results and tree diversity (Swift et al. 2004; Dumont et al. 2014; Poorter et al. 2015). Well-adapted trees and agroforestry practices are needed where increasing salinity and sodicity of drylands interact with drought periods and their potential increase due to climate change (Saqib et al. 2019).

In the Sahel, agriculture is often practised among scattered trees and shrubs, in the parkland agroforestry systems that constitute the predominant land use (Boffa 1999). The farming systems across the parklands generally involve interactions among trees, crops and livestock to deliver provisioning (Faye et al. 2011; Lamien et al. 1996) and regulating (Bayala et al. 2014) ecosystem services that underpin rural livelihoods (Sinclair 2017). The management of these systems reflects the ecological knowledge of farmers in such risk-prone environments, where crop residues are often preferentially used to feed livestock or as fuel rather than used for protecting soils and replenishing their fertility when used as mulch (Giller et al. 2009). The woody components of these systems, nevertheless, represents an important source of leaf and twig biomass for soil amendment (Diedhiou-Sall et al. 2013) including increasing and maintaining SOC (Bayala et al. 2006, 2020; Lufafa et al. 2008; Takimoto et al. 2008). Belowground organic inputs from root and rhizosphere turnover have been postulated as the primary source of SOC in the absence of soil tillage (McCormack et al. 2015).

2.4.5 Multifunctionality and Livelihoods

Facing the multiple SDGs, multifunctionality of agriculture is essential and trees play key roles in this (Leakey 2017; Catacutan et al. 2017). A review of peer-reviewed literature on trees in agricultural landscapes in Sub-Saharan Africa and the ecosystem services they enhance highlighted the need to manage trade-offs among impacts of trees on ES provision to reduce competition and increase complementarity between trees and crops (Kuyah et al. 2016). The 'multifunctionality gap' indicates that actual landscapes tend to operate substantially below their potential if all SDGs and their trade-offs are taken into account (Minang et al. 2021b).

Surveys in W Kenya (Reppin et al. 2020) showed that gaining self-sufficiency in firewood is the most important benefit associated with on-farm carbon accumulation. The use of exotic species for timber production represents a considerable trade-off between livelihood options and environmental goals. An evaluation of agroforestry programmes in Nepal (Aryal et al. 2019) concluded that programmes should not be limited on production of seedlings and plantation, but should incorporate soil fertility management, land productivity enhancement, water conservation and wise use, livelihood support and diversified production of food and forestry products.

In recent times, the continuous cultivation of crop fields and reduced fallow periods has led to a decline in SOC in most soils used for agriculture in the Sahel (Kintché et al. 2015). This, in turn, leads to declining productivity of what are often inherently infertile soils (Bai et al. 2008) because SOC is closely linked to nutrient cycling, aggregate stability, water and nutrient retention capacity and availability (Bationo et al. 2007; Tittonell and Giller 2013). While such degradation trends are manifested in the evident decline in tree density and diversity in some places in the Sahel (Gonzalez et al. 2012; Maranz 2009), there are other places where vegetation is recovering (Reij et al. 2009; Zomer et al. 2016). While for a long time these re-greening successes received little attention, they are now the subject of much research interest to generate information about the drivers (Ouedraogo et al. 2014; Reij and Garrity 2016) and impacts of tree cover change (Binam et al. 2015, 2017; Haglund et al. 2011; Sendzimir et al. 2011). These investigations have shown that regeneration of trees on farms can provide a safety-net through increasing cash income, caloric intake, dietary diversity, crop yield and livestock productivity in the drylands of West Africa (Adams et al. 2016; Binam et al. 2017; Sinare and Gordon 2015).

2.4.6 Hydroclimate Adaptation

Increasing tree cover influences both infiltration (groundwater recharge) and evapotranspiration with mixed effects on downstream water supply depending on the type of cropland on which tree cover increases (Clark et al. 2021), while it may generally have advantages downwind (Ellison et al. 2019; Ellison and Speranza 2020). Tree, shrub and forest-based landscape restoration can help provide landscape resilience in the Sahel through feedback effects on rainfall (Ellison and Speranza 2020). Statistically significant (but modest) improvements in soil water holding capacity are associated with the level of increase in soil organic carbon content attributable to agroforestry (rather than monoculture) cacao production systems in Sulawesi (Indonesia) (Gusli et al. 2020). An interesting contrast between drought sensitivity of cacao in Ghana and Sulawesi (Indonesia) has been reported: Abdulai et al. (2018) found that a combination of cacao with a fast-growing shallow-rooted tree in Ghana was more sensitive to years with reduced rainfall, while Schwendenmann et al. (2010) reported that in a throughfall reduction experiment to induce drought successful reduction of soil water content down to a soil depth of at least 2.5 m had limited effect on water use by cacao and Gliricidia in Sulawesi. Apparently, large differences in rooting depth of cacao between these situations cause very different conclusions about vulnerability and over-generalizations on the basis of limited and incompletely documented experiments may confuse current literature.

2.4.7 Restoration

Restoration efforts in Shinyanga (Tanzania) (Duguma et al. 2019) have effectively restored traditional institutions for landscape management, as basis for restoring tree cover and livelihoods. As such, this case still provides inspiration for other sites where 'restoration' is often seen as primarily a top-down agenda. Institutionally, the restoration agenda includes four levels of intensity and stakeholder involvement in people-centric restoration (Van Noordwijk et al. 2020a):

1. Ecological intensification within a land use system,
2. Recovery/regeneration, within a local social-ecological system,
3. Reparation/recuperation, within rules and rewards set by the national policy context,
4. Remediation, requiring international support and investment.

Appropriate actions reflect six requirements for effective restoration (an AF2 level concept, that are related to the key aspects of the AF1 concept (Fig. 2.5):

1. Community involvement, aligned with values and concerns,
2. Rights, major opportunities for restoring the multifunctionality of landscapes in the region are formed by resolution of existing conflicts over multiple claims to 'forest' land stewardship,
3. Knowledge and knowhow of sustainable land use practices,
4. Markets for inputs (incl. soil amendments, tree germplasm, labour) and outputs (access, bargaining position),
5. Local environmental impacts (often primarily through the water cycle and agrobiodiversity) and

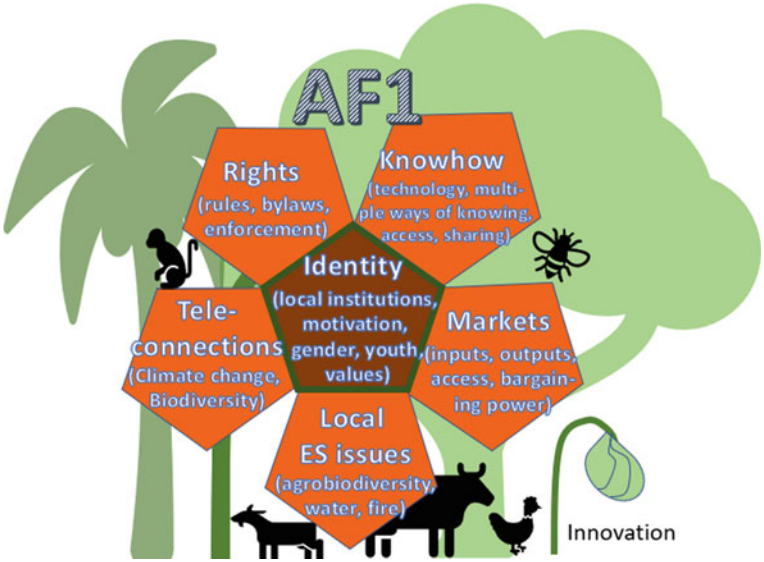

Fig. 2.5 The first, plot and farm-level agroforestry concept (AF1)

6. Global connectivity, including interactions with climate and global biodiversity agendas.

All six can be a 'starting point' for restoration interventions, but progress is typically limited by several (or all) of the others. In their analysis, all 17 Sustainable Development Goals can contribute to, and benefit from a coherent rights-based approach to restoration through agroforestry with specific technologies and choice of species dependent on local context and market access.

2.5 AF1-Plot/Farm-Level Use of Trees

2.5.1 Adaptation Planning

Three steps contribute to resilience: reduce exposure, reduce sensitivity and increase adaptive capacity (Nguyen et al. 2013). Guidelines for the construction of National Adaptation Plans include the full spectrum of forests and trees outside forest/ agroforestry in a local context (Meybeck et al. 2020). A range of countries in Asia and Africa have already made explicit reference to agroforestry in their National Adaptation Plans (Meybeck et al. 2021).

Many trees used in agroforestry have a wide distribution, with probably unrecognized genetic variation within the range that can be purposely used by propagating germplasm adapted to expected climate conditions during the life of the tree. Often, however, valuable germplasm sources are at risk. For example, a study (Salako et al. 2019) of current distribution and projected climate sensitivity of *Borassus aethiopum*, a palm declining as component of agroforestry in Benin, suggested loss of habitat suitability in the semi-arid zone where the species is currently widely distributed with higher abundance; attention to dispersal and propagation of drought-adapted populations of these palms is warranted.

Whereas climate change impacts on crops grown in monocultures can reasonably well be projected with process-based crop models, robust models for complex agroforestry systems are not available (Luedeling et al. 2014), at least in part due to effects on microclimate that remain unquantified in most studies. A study in Vietnam (Nguyen et al. 2013) found that rice and rain-fed crops suffered over 40% yield losses in years of extreme drought or flood, but tree-based systems and cattle were less affected. Farmers in remote villages went into the forest to earn a living in difficult times caused by extreme weather, while those with better road access focused on trading and urban activities in such periods.

A study in northern and central Vietnam (Simelton et al. 2015) found that farms with trees had shorter recovery time after most types of natural disasters, except for cold spells, demonstrating economic and environmental buffers. Smallholder farming households in semi-arid Isiolo County, Kenya have benefited from their agroforestry trees during drought and flood events by reduced sensitivity and increased opportunities to adapt by providing critical tree products and financial benefits (fruit, food, firewood, construction materials, fodder, traditional medicines, money from sales of fruit products) (Quandt 2020). Pandey et al. (2015) discussed 35 indicators (8 for exposure, 12 for sensitivity and 15 for adaptive capacity) for agroforestry and land uses without trees in the Himalayan region in India; small land holdings restricted the contribution of agroforestry practices to these indicators, with poverty as the key driver for vulnerability.

2.5.2 Climate-Smart in Practice

Climate-smart agriculture (CSA) is a pathway towards development and food security built on three pillars: food security, adaptation and mitigation (van Wijk et al. 2020). There are many opportunities for capturing synergies between the pillars of climate-smart agriculture, but also many situations where trade-offs are inevitable (Newaj et al. 2016). In comparison with monoculture horticultural systems, a literature review of agroforestry systems documented better use of water, soil and light, can help reduce the application of herbicides, fungicides, pesticides, fertilizers, increasing food security, biodiversity protection and climatic change adaptation (Colmenares et al. 2020). Whereas many technologies are available to help farmers better cope with climate risks, including drought, improving farmers' access to these technologies, while strengthening incentives around their adoption, remains the more significant challenge. Despite millions of dollars of investment, adoption rates of new agricultural technologies in much of eastern and southern Africa remain low (Rosenstock et al. 2019b). Kimaro et al. (2019) identified steps that help in improving this track record of what is labelled as climate-smart agriculture (CSA): select appropriate indicators, ensure designs are robust for heterogeneity, examine trade-offs and conduct participatory evaluation of CSA on farmers' field sites.

Groundwork of participatory action-research on CSA in West Africa revealed three critical factors to be considered: (1) Building strong partnerships to co-design and develop agricultural systems that improve ecosystem and population resilience, (2) Key stakeholders (researchers, farmers, development agents and students) capacity strengthening through vocational and academic training and (3) Using climate information for livelihood planning at all scales (Bayala et al. 2021).

Farmer awareness and perceptions of climate change and positive roles of trees may not be homogeneous within a local farming community (Lasco et al. 2016; Sanogo et al. 2017). Dawson et al. (2014) discussed recent agroforestry interventions to support livestock keeping in East Africa that have included the planting of mostly exotic tree-fodders, and where most parts of the region are expected to become drier in the next decades, although smaller areas may become wetter. Wider cultivation and improved management of fodder trees provide adaptation and mitigation opportunities in the region, but these are generally not well quantified and there are clear opportunities for increasing productivity and resilience through diversification, genetic improvement, improved farm-input delivery and better modelling of future scenarios.

Amadu et al. (2020) found a modest, but positive and statistically significant maize yield effect for participants of a climate-smart agriculture (CSA) programme implemented from 2009 to 2014 in southern Malawi. A study in W. Kenya (De Giusti et al. 2019) differentiated between timber and fuelwood as agroforestry products with long vs short residence times once harvested and concluded that although agroforestry in the area was not perceived to be more profitable than traditional agricultural practices, it plays an important economic and environmental role by supporting subsistence through provision of fuelwood and could relieve pressure upon common forest resources.

2.6 Concluding Remarks

While, historically, agroforestry has its roots at the farm-level AF1 concept and only gradually explored landscape-level AF2 and policy-level AF3 aspects, current bottlenecks to the full acceptance of and active support for the match between agroforestry and the evolving climate change mitigation and adaptation agendas in Asia and Africa may be formed by

- Continued segregation of agriculture and forestry as separate sectors,
- Persistence of mitigation and adaptation as dependent on separate funding streams and
- Consumer pressure on commodity value chains that cares about 'deforestation' and/or 'lack of living wage' in producing countries, but not on integrated social-

ecological solutions in landscapes and jurisdictions that have partial authority to manage towards SDGs.

Stronger links are needed across the vertical (individuals, communities, subnational, national and global) scale of Fig. 2.1 and the issue-cycle (data, feedbacks, institutions and goals) leverage points within and across each scale. Agroforestry can progress if efforts succeed to (1) help farmers + corporate sectors + consumers to get better connected where products are exchanged for finance along a chain, but 'relational values' travel in both directions (van Noordwijk 2021) and current certification systems involve high transaction costs and yet don't build the levels if trust needed, and (2) formal government data, rules, rights and investment effectively connect 'all land uses', transcending current categorizations. Steps are being made in Asia and Africa, but much remains to be done.

References

Abdulai I, Vaast P, Hoffmann MP, Asare R, Jassogne L, Van Asten P, Rötter RP, Graefe S (2018) Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Glob Chang Biol 24(1):273–286

Adams C, Rodrigues S, Calmon M, Kumar C (2016) Impacts of large-scale forest restoration on socioeconomic status and local livelihoods: what we know and do not know. Biotropica 48: 731–744

Amadu FO, Miller DC, McNamara PE (2020) Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: evidence from southern Malawi. Ecol Econ 167:106443

Angelsen A, Martius C, De Sy V, Duchelle AE, Larson AM, Pham TT (2018) Conclusions: lessons for the path to a transformational REDD+. CIFOR, Bogor

Aryal K, Thapa PS, Lamichhane D (2019) Revisiting agroforestry for building climate resilient communities: a case of package-based integrated agroforestry practices in Nepal. Emerg Sci J 3(5):303–311

Asubonteng KO, Pfeffer K, Ros-Tonen MA, Baud I, Benefoh DT (2020) Integration versus segregation: structural dynamics of a smallholder-dominated mosaic landscape under tree-crop expansion in Ghana. Appl Geogr 118:102201

Bai ZG, Dent DL, Olsson L, Schaepman ME (2008) Proxy global assessment of land degradation. Soil Use Manag 24(3):223–234

Bationo A, Kihara J, Vanlauwe B, Waswa B, Kimetu J (2007) Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric Syst 94(1):13–25

Bayala J, Balesdent J, Marol C, Zapata F, Teklehaimanot Z, Ouedraogo SJ (2006) Relative contribution of trees and crops to soil carbon content in a parkland system in Burkina Faso using variations in natural 13C abundance. Nutr Cycl Agroecosyst 76:193–201

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Bayala J, Sanou J, Teklehaimanot Z, Ouedraogo SJ, Kalinganire A, Coe R, van Noordwijk M (2015) Advances in knowledge of processes in soil–tree–crop interactions in parkland systems in the West African Sahel: a review. Agric Ecosyst Environ 205:25–35

Bayala J, Sanou J, Bazié HR, Coe R, Kalinganire A, Sinclair FL (2020) Regenerated trees in farmers' fields increase soil carbon across the Sahel. Agrofor Syst 94:401–415. https://doi.org/10.1007/s10457-019-00403-6

Bayala J, Ky-Dembele C, Dayamba SD, Somda J, Ouédraogo M, Diakite A, Chabi A, Alhassane A, Bationo AB, Buah SSJ, Sanogo D, Tougiani A, Traore K, Zougmoré RB, Rosenstock TS (2021) Multi-actors' co-implementation of climate-smart village approach in West Africa: achievements and lessons learnt. Front Sustain Food Syst 5:637007. https://doi.org/10.3389/fsufs.2021.637007

Bernard F, Minang PA, van Noordwijk M, Freeman OE, Duguma LA (eds) (2013) Towards a landscape approach for reducing emissions: a substantive report of the reducing emissions from all land uses (REALU) project. World Agroforestry Centre, Nairobi, p 119

Binam JN, Place F, Kalinganire A, Sigue H, Boureima M, Tougiani A, Dakouo J, Mounkoro B, Sanogo D, Badji M, Diop M, Bationo BA, Haglund E (2015) Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa. Environ Econ Policy Stud 17(4):543–575

Binam JN, Place F, Djalal AA, Kalinganire A (2017) Effects of local institutions on the adoption of agroforestry innovations: evidence of farmer managed natural regeneration and its implications for rural livelihoods in the Sahel. Agric Food Econ 5:2

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa. FAO Conservation Guide 34. FAO, Rome

Brockhaus M, Di Gregorio M, Djoudi H, Moeliono M, Pham TT, Wong GY (2021) The forest frontier in the Global South: climate change policies and the promise of development and equity. Ambio 50(12):2238–2255

Cardinael R, Cadisch G, Gosme M, Oelbermann M, van Noordwijk M (2021) Climate change mitigation and adaptation in agriculture: why agroforestry should be part of the solution. Agric Ecosyst Environ 319:107555

Carter S, Arts B, Giller KE, Golcher CS, Kok K, De Koning J, van Noordwijk M, Reidsma P, Rufino MC, Salvini G, Verchot L (2018) Climate-smart land use requires local solutions, transdisciplinary research, policy coherence and transparency. Carbon Manage 9(3):291–301

Castro P, Azul AM, Leal Filho W, Azeiteiro UM (eds) (2019) Climate change-resilient agriculture and agroforestry: ecosystem services and sustainability. Springer, Cham

Catacutan DC, van Noordwijk M, Nguyen TH, Öborn I, Mercado AR (2017) Agroforestry: contribution to food security and climate-change adaptation and mitigation in Southeast Asia. White Paper. World Agroforestry Centre (ICRAF), Bogor

Charles RL, Munishi PKT, Nzunda EF (2013) Agroforestry as adaptation strategy under climate change in Mwanga District, Kilimanjaro, Tanzania. Int J Environ Prot 3(11):29–38

Clark B, DeFries R, Krishnaswamy J (2021) India's commitments to increase tree and forest cover: consequences for water supply and agriculture production within the Central Indian Highlands. Watermark 13(7):959. https://doi.org/10.3390/w13070959

Colmenares OM, Brindis RC, Verduzco CV, Grajales MP, Gómez MU (2020) Horticultural agroforestry systems recommended for climate change adaptation: a review. Agric Rev 41(1): 14–24

Dawson IK, Carsan S, Franzel S, Kindt R, Van Breugel P, Graudal L, Lillesø JPB, Orwa C, Jamnadass R (2014) Agroforestry, livestock, fodder production and climate change adaptation and mitigation in East Africa: issues and options. World Agroforestry Center, Nairobi

De Giusti G, Kristjanson P, Rufino MC (2019) Agroforestry as a climate change mitigation practice in smallholder farming: evidence from Kenya. Clim Chang 153(3):379–394

De Sy V, Herold M, Brockhaus M, Di Gregorio M, Ochieng RM (2018) Information and policy change: data on drivers can drive change – if used wisely. In: Angelsen A, Martius C, De Sy V, Duchelle AE, Larson AM, Pham TT (eds) Transforming REDD+: lessons and new directions. Bogor, CIFOR, pp 55–66

De Zoysa M, Inoue M (2014) Climate change impacts, agroforestry adaptation and policy environment in Sri Lanka. Open J Forestry 4(5):439

Diedhiou-Sall S, Dossa EL, Badiane AN, Assigbetsee KB, Diedhiou I, Ndiaye NAS et al (2013) Microbiology and macrofaunal activity in soil beneath shrub canopies during residue decomposition in agroecosystems of the Sahel. Soil Sci Soc Am J 77:501–511

Duchelle AE, Simonet G, Sunderlin WD, Wunder S (2018) What is REDD+ achieving on the ground? Curr Opin Environ Sustain 32:134–140. https://doi.org/10.1016/j.cosust.2018.07.001

Duguma LA, Minang PA, van Noordwijk M (2014a) Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. Environ Manag 54(3):420–432

Duguma LA, Wambugu SW, Minang PA, van Noordwijk M (2014b) A systematic analysis of enabling conditions for synergy between climate change mitigation and adaptation measures in developing countries. Environ Sci Policy 42:138–148

Duguma LA, Minang PA, Kimaro AA, Otsyina R, Mpanda M (2019) Shinyanga: blending old and new agroforestry to integrate development, climate change mitigation and adaptation in Tanzania. In: Sustainable development through trees on farms: agroforestry in its fifth decade, Bogor, Indonesia, p 137–149

Duguma LA, Minang PA, Watson C, Nath AJ, Muthee KW, van Noordwijk M, Mutune JM (2022) Agroforestry as a key intervention to achieve nationally determined contribution (NDC) targets

Dumont ES, Gnahoua GM, Ohouo L, Sinclair FL, Vaast P (2014) Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. Agrofor Syst 88(6): 1047–1066

Elagib NA, Al-Saidi M (2020) Balancing the benefits from the water–energy–land–food nexus through agroforestry in the Sahel. Sci Total Environ 742:140509

Ellison D, Speranza CI (2020) From blue to green water and back again: promoting tree, shrub and forest-based landscape resilience in the Sahel. Sci Total Environ 739:140002

Ellison D, Wang-Erlandsson L, van der Ent R, van Noordwijk M (2019) Upwind forests: managing moisture recycling for nature-based resilience. Unasylva 70(251):14–26

Faye MD, Weber JC, Tougiani A, Boureima M, Larwanou M, Bationo AB, Diallo BO, Sigué H, Dakouo J-M, Samaké O, Sonogo-Diaité D (2011) Farmers' preferences for tree functions and species in the West African Sahel. For Trees Livelihoods 20:113–136

Garrity DP, Bayala J (2019) Zinder: farmer-managed natural regeneration of Sahelian parklands in Niger. In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor, pp 153–174

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114(1):23–34

Gonzalez P, Tucker CJ, Sy H (2012) Tree density and species decline in the African Sahel attributable to climate. J Arid Environ 78:55–64

Gusli S, Sumeni S, Sabodin R, Muqfi IH, Nur M, Hairiah K, Useng D, van Noordwijk M (2020) Soil organic matter, mitigation of and adaptation to climate change in cocoa–based agroforestry systems. Landscape 9(9):323

Haglund E, Ndjeunga J, Snook L, Pasternak D (2011) Dry land tree management for improved household livelihoods: farmer managed natural regeneration in Niger. J Environ Manag 92(7): 1696–1705

Henders S, Persson UM, Kastner T (2015) Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Environ Res Lett 10(12): 125012

Hoang MH, Do TH, Pham MT, van Noordwijk M, Minang PA (2013) Benefit distribution across scales to reduce emissions from deforestation and forest degradation (REDD+) in Vietnam. Land Use Policy 31:48–60

Kimaro AA, Sererya OG, Matata P, Uckert G, Hafner J, Graef F, Sieber S, Rosenstock TS (2019) Understanding the multidimensionality of climate-smartness: examples from agroforestry in Tanzania. In: The climate-smart agriculture papers. Springer, Cham, pp 153–162

Kintché K, Guibert H, Bonfoh B, Tittonell P (2015) Long-term decline in soil fertility and responsiveness to fertiliser as mitigated by short fallow periods in sub-Sahelian area of Togo. Nutr Cycl Agroecosyst 101(3):333–350

Koffi G, Worms P (2021) Niger formally adopts farmer-managed natural regeneration. Blog. https://www.worldagroforestry.org/blog/2021/01/12/niger-formally-adopts-farmer-managed-natural-regeneration

Korhonen-Kurki K, Brockhaus M, Sehring J, Di Gregorio M, Assembe-Mvondo S, Babon A, Bekele M, Benn V, Gebara MF, Kambire HW, Kengoum F (2019) What drives policy change for REDD+? A qualitative comparative analysis of the interplay between institutional and policy arena factors. Clim Pol 19(3):315–328

Kuyah S, Öborn I, Jonsson M, Dahlin AS, Barrios E, Muthuri C, Malmer A, Nyaga J, Magaju C, Namirembe S, Nyberg Y (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. Int J Biodivers Sci Ecosyst Serv Manage 12(4):255–273

Lamien N, Sidibé A, Bayala J (1996) Use and commercialization of non-timber forest products in western Burkina Faso. In: Leakey RRB, Temu AB, Melnyk M (eds) Domestication and commercialization of non-timber forest products in agroforestry systems. FAO, Rome, pp 51–63

Larson AM, Mausch K, Bourne M, Luttrell C, Schoneveld G, Cronkleton P, Locatelli B, Catacutan D, Cerutti P, Chomba S, Djoudi H et al (2021) Hot topics in governance for forests and trees: towards a (just) transformative research agenda. Forest Policy Econ 131:102567

Lasco RD, Delfino RJP, Catacutan DC, Simelton ES, Wilson DM (2014a) Climate risk adaptation by smallholder farmers: the roles of trees and agroforestry. Curr Opin Environ Sustain 6:83–88

Lasco RD, Delfino RJP, Espaldon MLO (2014b) Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. Wiley Interdiscip Rev 5(6):825–833

Lasco RD, Espaldon MLO, Habito CMD (2016) Smallholder farmers' perceptions of climate change and the roles of trees and agroforestry in climate risk adaptation: evidence from Bohol, Philippines. Agrofor Syst 90(3):521–540

Leakey R (2017) Multifunctional agriculture: achieving sustainable development in Africa. Academic, New York

Lin T, Catacutan DC, van Noordwijk M, Finlayson RF, Rogel CN, Orencio P (2021) State and outlook of agroforestry in ASEAN –status, trends and outlook 2030 and beyond. FAO, Bangkok

Luedeling E, Kindt R, Huth NI, Koenig K (2014) Agroforestry systems in a changing climate—challenges in projecting future performance. Curr Opin Environ Sustain 6:1–7

Lufafa A, Diedhiou I, Samaba SAN, Séné M, Khouma M, Kizito F, Dick RP, Dossa E, Noller JS (2008) Carbon stocks and patterns in native shrub communities of Senegal's Peanut Basin. Geoderma 146:75–82

Maranz S (2009) Tree mortality in the African Sahel indicates an anthropogenic ecosystem displaced by climate change. J Biogeogr 36:1181–1193

Martius C, Duchelle AE (2021) REDD+: combating climate change with forest science. FTA highlights of a decade 2011–2021 series. The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), Bogor

Mbow C, Smith P, Skole D, Duguma LA, Bustamante M (2014a) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr Opin Environ Sustain 6:8–14

Mbow C, van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014b) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67

Mbow C, van Noordwijk M, Prabhu R, Simons T (2014c) Knowledge gaps and research needs concerning agroforestry's contribution to sustainable development goals in Africa. Curr Opin Environ Sustain 6:162–170

McCall MK, Minang PA (2005) Assessing participatory GIS for community-based natural resource management: claiming community forests in Cameroon. Geogr J 171(4):340–356. https://doi.org/10.1111/j.1475-4959.2005.00173.x

McCormack ML, Dickie IA, Eissenstat DM, Fahey TJ, Fernandez CW, Guo D, Helmisaari HS, Hobbie EA, Iversen CM, Jackson RB, Leppälammi-Kujansuu J (2015) Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes. New Phytol 207(3):505–518

Meadows D (1999) Leverage points: places to intervene in a system. Solut Sustain Desirable Future 1:41–49

Mertz O, Müller D, Sikor T, Hett C, Heinimann A, Castella JC, Lestrelin G, Ryan CM, Reay DS, Schmidt-Vogt D, Danielsen F (2012) The forgotten D: challenges of addressing forest degradation in complex mosaic landscapes under REDD+. Danish J Geogr 112(1):63–76

Meybeck A, Gitz V, Wolf J, Wong T (2020) Addressing forestry and agroforestry in National Adaptation Plans: supplementary guidelines. Food and Agriculture Organization, Rome

Meybeck A et al (2021) Adaptation to climate change with forests, trees and agroforestry. FTA highlights of a decade 2011–2021 series. The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), Bogor

Minang PA, van Noordwijk M (2014) The political economy of Readiness for REDD+. Clim Pol 14(6):677–684

Minang PA, van Noordwijk M, Meyfroidt P, Agus F, Dewi S (2010) Emissions embodied in trade (EET) and land use in tropical forest margins. Policy Brief-ASB Partnership for the Tropical Forest Margins, p 17

Minang PA, Duguma LA, Bernard F, Mertz O, van Noordwijk M (2014) Prospects for agroforestry in REDD+ landscapes in Africa. Curr Opin Environ Sustain 6:78–82

Minang PA, Duguma LA, van Noordwijk M, Prabhu R, Freeman OE (2015) Enhancing multifunctionality through system improvement and landscape democracy processes: a synthesis. In: Minang PA, van Noordwijk M, Freeman OE, Mbow C, de Leeuw J, Catacutan D (eds) Climate-smart landscapes: multifunctionality in practice. World Agroforestry, Bogor, pp 389–405

Minang PA, Duguma LA, Leimona B, van Noordwijk M, Catacutan D, Ickowitz A, Dewi S, Johana F, Rizvi J, Barletti S et al (2021a) Governing forests, agroforestry and trees for delivering on the SDGs. FTA highlights of a decade 2011–2021 series. The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), Bogor

Minang PA, Duguma LA, van Noordwijk M, Sunderland T, Reed J, Leimona B, Ickowitz A, Wainaina P, Dewi S, Cola C et al (2021b) Multi-functional landscapes for sustainable development. FTA highlights of a decade 2011–2021 series. The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), Bogor

Moeliono M, Brockhaus M, Gallemore CT, Bimo D, Cynthia M, Efrian M, Pham TT (2020) REDD + in Indonesia: a new mode of governance or just another project? Forest Policy Econ 121: 102316

Mulyoutami E, Lusiana B, van Noordwijk M (2020) Gendered migration and agroforestry in Indonesia: livelihoods, labor, know-how, networks. Landscape 9(12):529

Namirembe S, Leimona B, van Noordwijk M, Minang PA (2017) Co-investment in ecosystem services: global lessons from payment and incentive schemes. World Agroforestry Centre, Nairobi

Newaj R, Chaturvedi OP, Handa AK (2016) Recent development in agroforestry research and its role in climate change adaptation and mitigation. Indian J Agroforest 18(1):1–9

Ngoma H, Angelsen A, Carter S, Roman-Cuesta RM (2018) Climate-smart agriculture: will higher yields lead to lower deforestation? In: Angelsen A, Martius C, De Sy V, Duchelle AE, Larson AM, Pham TT (eds) Transforming REDD+: lessons and new directions. CIFOR, Bogor, pp 175–187

Nguyen Q, Hoang MH, Öborn I, van Noordwijk M (2013) Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. Clim Chang 117(1):241–257

Nyong AP, Ngankam TM, Felicite TL (2020) Enhancement of resilience to climate variability and change through agroforestry practices in smallholder farming systems in Cameroon. Agrofor Syst 94(3):687–705

Ong CK, Black C, Wilson J (eds) (2015) Tree-crop interactions: agroforestry in a changing climate. CAB International, Wallingford

Ordonez JC, Luedeling E, Kindt R, Tata HL, Harja D, Jamnadass R, van Noordwijk M (2014) Constraints and opportunities for tree diversity management along the forest transition curve to achieve multifunctional agriculture. Curr Opin Environ Sustain 6:54–60

Ouedraogo I, Runge J, Eisenberg J, Barron J, Kabore S (2014) The re-greening of the Sahel: natural cyclicity or human-induced change? Landscape 3:1075–1090
Pandey R, Meena D, Aretano R, Satpathy S, Semeraro T, Gupta AK, Rawat S, Zurlini G (2015) Socio-ecological vulnerability of smallholders due to climate change in mountains: agroforestry as an adaptation measure. Change Adapt Socio-Ecol Syst 2(1):3
Pendrill F, Persson UM, Godar J, Kastner T, Moran D, Schmidt S, Wood R (2019) Agricultural and forestry trade drives large share of tropical deforestation emissions. Glob Environ Chang 56:1–10
Pham TT, Moeliono M, Yuwono J, Dwisatrio B, Gallo P (2021) REDD+ finance in Brazil, Indonesia and Vietnam: Stakeholder perspectives between 2009-2019. Glob Environ Chang 70:102330
Poorter L, van der Sande MT, Thompson J, Arets EJ, Alarcón A, Álvarez-Sánchez J, Ascarrunz N, Balvanera P, Barajas-Guzmán G, Boit A, Bongers F et al (2015) Diversity enhances carbon storage in tropical forests. Glob Ecol Biogeogr 24(11):1314–1328
Prasad R, Newaj R, Chavan SB, Dhyani SK (2014) Agroforestry land use: a way forward for reducing carbon footprint in agriculture. Indian J Agroforest 16(2):15–23
Purwanto E, Santoso H, Jelsma I, Widayati A, Nugroho HY, van Noordwijk M (2020) Agroforestry as policy option for forest-zone oil palm production in Indonesia. Landscape 9(12):531
Quandt A (2020) Contribution of agroforestry trees for climate change adaptation: narratives from smallholder farmers in Isiolo, Kenya. Agrofor Syst 94(6):2125–2136
Raj A, Jhariya MK, Yadav DK, Banerjee A (eds) (2020) Climate change and agroforestry systems: adaptation and mitigation strategies. Apple Academic Press, Oakville
Reij C, Garrity D (2016) Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. Biotropica 48(6):834–843
Reij C, Tappan G, Smale M (2009) Re-greening the Sahel: farmer-led innovation in Burkina Faso and Niger. In: Reij C, Tappan G, Smale M (eds) Agro-environmental transformation in the Sahel: another kind of "Green Revolution" IFPRI Discussion Paper. International Food Policy Research Institute, Washington, pp 53–58
Reppin S, Kuyah S, de Neergaard A, Oelofse M, Rosenstock TS (2020) Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. Agrofor Syst 94(1): 203–220
Rosenstock TS, Wilkes A, Jallo C, Namoi N, Bulusu M, Suber M, Mboi D, Mulia R, Simelton E, Richards M, Gurwick N (2019a) Making trees count: measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. Agric Ecosyst Environ 284: 106569
Rosenstock TS, Lamanna C, Namoi N, Arslan A, Richards M (2019b) What is the evidence base for climate-smart agriculture in East and Southern Africa? A systematic map. In: The climate-smart agriculture papers. Springer, Cham, pp 143–151
Salako VK, Vihotogbé R, Houéhanou T, Sodé IA, Kakaï RG (2019) Predicting the potential impact of climate change on the declining agroforestry species Borassus aethiopum Mart. in Benin: a mixture of geostatistical and SDM approach. Agrofor Syst 93(4):1513–1530
Sanogo K, Binam J, Bayala J, Villamor GB, Kalinganire A, Dodiomon S (2017) Farmers' perceptions of climate change impacts on ecosystem services delivery of parklands in southern Mali. Agrofor Syst 91:345–361
Saqib M, Akhtar J, Abbas G, Murtaza G (2019) Enhancing food security and climate change resilience in degraded land areas by resilient crops and agroforestry. In: Climate change-resilient agriculture and agroforestry. Springer, Cham, pp 283–297
Schwendenmann L, Veldkamp E, Moser G, Hölscher D, Köhler M, Clough Y, Anas I, Djajakirana G, Erasmi S, Hertel D, Leitner D (2010) Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. Glob Chang Biol 16(5): 1515–1530

Sendzimir J, Reij CP, Magnuszewski P (2011) Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder Regions of Niger. Ecol Soc 16(3):301. https://doi.org/10.5751/ES-04198-160301

Sharma N, Bohra B, Pragya N, Ciannella R, Dobie P, Lehmann S (2016) Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. Food Energy Secur 5(3):165–183

Sheppard JP, Bohn Reckziegel R, Borrass L, Chirwa PW, Cuaranhua CJ, Hassler SK, Hoffmeister S, Kestel F, Maier R, Mälicke M, Morhart C (2020) Agroforestry: an appropriate and sustainable response to a changing climate in Southern Africa? Sustain For 12(17):6796

Simelton E, Dam BV, Catacutan D (2015) Trees and agroforestry for coping with extreme weather events: experiences from northern and central Vietnam. Agrofor Syst 89(6):1065–1082

Sinare H, Gordon LJ (2015) Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa. Agric Ecosyst Environ 200:186–199

Sinclair FL (2017) Systems science at the scale of impact: reconciling bottom-up participation with the production of widely applicable research outputs. In: Oborn I, Vanlauwe B, Phillips M, Thomas R, Brooijmans W, Atta-Krah K (eds) Sustainable intensification in smallholder agriculture: an integrated systems research approach. Earthscan, London, pp 43–57

Skole DL, Mbow C, Mugabowindekwe M, Brandt MS, Samek JH (2021) Trees outside of forests as natural climate solutions. Nat Clim Chang 11(12):1013–1016

Smith P, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, Jafari M, Masera O, Mbow C, Ravindranath NH (2014) Chapter 11: agriculture, forestry and other land use (AFOLU). In: Climate change 2014: mitigation of climate change. IPCC Working Group III Contribution to AR5. Cambridge University Press, Cambridge

Swift MJ, Izac AM, van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric Ecosyst Environ 104(1):113–134

Takimoto A, Nair PKR, Nair VD (2008) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166

Tewari JC, Ram M, Roy MM, Dagar JC (2014) Livelihood improvements and climate change adaptations through agroforestry in hot arid environments. In: Agroforestry systems in India: livelihood security & ecosystem services. Springer, New Delhi, pp 155–183

Thamo T, Pannell DJ (2016) Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence. Clim Pol 16(8):973–992

Tittonell P, Giller KE (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res 143:76–90

Tomich TP, van Noordwijk M, Vosti SA, Witcover J (1998) Agricultural development with rainforest conservation: methods for seeking best bet alternatives to slash-and-burn, with applications to Brazil and Indonesia. Agric Econ 19(1-2):159–174

Tschora H, Cherubini F (2020) Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. Glob Ecol Conserv 22:e00919

van Noordwijk M (2018) Agroforestry as part of climate change response. IOP Conf Ser 200(1): 012002

van Noordwijk M (2021) Agroforestry-based ecosystem services: reconciling values of humans and nature in sustainable development. Landscape 10(7):699

van Noordwijk M, Catacutan D (2017) Common but differentiated responsibility for restoration and avoided degradation of commons: who pays for basic rights? In: Co-investment in ecosystem services: global lessons from payment and incentive schemes. World Agroforestry Centre (ICRAF), Nairobi

van Noordwijk M, Suyamto DA, Lusiana B, Ekadinata A, Hairiah K (2008) Facilitating agroforestation of landscapes for sustainable benefits: tradeoffs between carbon stocks and local development benefits in Indonesia according to the FALLOW model. Agric Ecosyst Environ 126(1):98–112

van Noordwijk M, Hoang MH, Neufeldt H, Öborn I, Yatich T (eds) (2011) Reducing vulnerability in multifunctional landscapes. World Agroforestry (ICRAF), Nairobi, p 136 van Noordwijk M, Leimona B, Jindal R, Villamor GB, Vardhan M, Namirembe S, Catacutan D, Kerr J, Minang PA, Tomich TP (2012a) Payments for environmental services: evolution toward efficient and fair incentives for multifunctional landscapes. Annu Rev Environ Resour 37:389–420

van Noordwijk M, Tata HL, Xu J, Dewi S, Minang PA (2012b) Segregate or integrate for multifunctionality and sustained change through rubber-based agroforestry in Indonesia and China. In: Agroforestry-the future of global land use. Springer, Dordrecht, pp 69–104

van Noordwijk M, Agus F, Dewi S, Purnomo H (2014a) Reducing emissions from land use in Indonesia: motivation, policy instruments and expected funding streams. Mitig Adapt Strateg Glob Chang 19(6):677–692

van Noordwijk M, Matthews R, Agus F, Farmer J, Verchot L, Persch S, Tata HL, Lusiana B, Widayati A, Dewi S (2014b) Mud, muddle and models in the knowledge value-chain to action on tropical peatland conservation. Mitig Adapt Strateg Glob Chang 19(6):887–905

van Noordwijk M, Bayala J, Hairiah K, Lusiana B, Muthuri C, Khasanah N, Mulia R (2014c) Agroforestry solutions for buffering climate variability and adapting to change. In: Fuhrer J, Gregory PJ (eds) Climate change impact and adaptation in agricultural systems. CABI, Wallingford, pp 216–232

van Noordwijk M, Coe R, Sinclair F (2016a) Central hypotheses for the third agroforestry paradigm within a common definition. World Agroforestry Centre (ICRAF), Nairobi

van Noordwijk M, Kim YS, Leimona B, Hairiah K, Fisher LA (2016b) Metrics of water security, adaptive capacity, and agroforestry in Indonesia. Curr Opin Environ Sustain 21:1–8

van Noordwijk M, Duguma LA, Dewi S, Leimona B, Catacutan DC, Lusiana B, Öborn I, Hairiah K, Minang PA (2018) SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? Curr Opin Environ Sustain 34:33–42

van Noordwijk M, Gitz V, Minang PA, Dewi S, Leimona B, Duguma L, Pingault N, Meybeck A (2020a) People-centric nature-based land restoration through agroforestry: a typology. Landscape 9(8):251

van Noordwijk M, Ekadinata A, Leimona B, Catacutan D, Martini E, Tata HL, Öborn I, Hairiah K, Wangpakapattanawong P, Mulia R, Dewi S (2020b) Agroforestry options for degraded landscapes in Southeast Asia. In: Agroforestry for degraded landscapes. Springer, Singapore, pp 307–347

van Noordwijk M, Speelman EN, Hofstede GJ, Farida A, Abdurrahim AY, Miccolis A, Lukman A, Nduhiu C, Lagneaux E, Andreotti F, Kimbowa G, Assogba G, Best L, Tanika L, Githinji M, Rosero P, Satnarain U, Sari RR, Adiwibowo S, Ligtenberg A, Peña-Claros A, Muthuri CW, van Oel A, Peña-Claros A, Purwanto E, van Oel A, Rozendaal D, Suprayogo D, Teuling A (2020c) Sustainable agro-forestry management: changing the game. Landscape 9(243):1–38

van Noordwijk M, Coe R, Sinclair FL, Luedeling E, Bayala J, Muthuri CW, Cooper P, Kindt R, Duguma L, Lamanna C, Minang PA (2021) Climate change adaptation in and through agroforestry: four decades of research initiated by Peter Huxley. Mitig Adapt Strateg Glob Chang 26(5):1–33

van Noordwijk M, van Oel A, Muthuri CW, Sari RR, Satnarain U, Rosero P, Githinji M, Tanika L, Best L, Assogba G, Kimbowa G, Andreotti F, Lagneaux E, Nduhiu C, Lukman A, Miccolis A, Abdurrahim AY, Farida A, Speelman EN, Hofstede GJ (2022a) Mimicking nature to reduce agricultural impact on water cycles: a set of mimetrics. Outlook Agric 51:114–128

van Noordwijk M, Leimona B, Pham TT, Duguma LA, Dewi S, Minang PA (2022b) Carbon footprints, informed consumer decisions and shifts towards responsible agriculture, forestry and other land uses? Carbon Footprints 1:4. https://doi.org/10.20517/cf.2022.02

Van Oosterzee P, Blignaut J, Bradshaw CJ (2012) iREDD hedges against avoided deforestation's unholy trinity of leakage, permanence and additionality. Conserv Lett 5(4):266–273

van Wijk MT, Merbold L, Hammond J, Butterbach-Bahl K (2020) Improving assessments of the three pillars of climate smart agriculture: current achievements and ideas for the future. Front Sustainable Food Syst 4:148

Vanderhaegen K, Verbist B, Hundera K, Muys B (2015) REALU vs. REDD+: Carbon and biodiversity in the Afromontane landscapes of SW Ethiopia. For Ecol Manag 343:22–33
Verchot LV, van Noordwijk M, Kandji S, Tomich TP, Ong CK, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm CA (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strateg Glob Chang 12(5):901–918
Verchot L, De Sy V, Romijn E, Herold M, Coppus R (2018) Forest restoration: getting serious about the 'plus' in REDD+. In: Angelsen A, Martius C, De Sy V, Duchelle AE, Larson AM, Pham TT (eds) Transforming REDD+: lessons and new directions. CIFOR, Bogor, pp 189–202
Vignola R, Harvey CA, Bautista-Solis P, Avelino J, Rapidel B, Donatti C, Martinez R (2015) Ecosystem-based adaptation for smallholder farmers: definitions, opportunities and constraints. Agric Ecosyst Environ 211:126–132
Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (2000) Land use, land-use change and forestry. Cambridge University Press, Cambridge, p 375
Wong GY, Luttrell C, Loft L, Yang A, Pham TT, Naito D, Assembe-Mvondo S, Brockhaus M (2019) Narratives in REDD+ benefit sharing: examining evidence within and beyond the forest sector. Clim Pol 19(8):1038–1051
Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6(1):1–12

Chapter 3
Farmer-Managed Natural Regeneration in Africa: Evidence for Climate Change Mitigation and Adaptation in Drylands

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Abstract The size of drylands in Africa is constantly increasing following the increase of the population, land use and practices used in the daily activities to sustain community livelihood. Climate change and erratic weather conditions are also expected to contribute to further land degradation, expanding dryland ecosystems. Land degradation undermines the range of ecosystem services on which dryland communities depend on. This chapter highlights challenges faced by dryland communities in Africa, which might be exacerbated by climate change. Throughout the chapter, evidence is presented on ways to transform drylands into productive, profitable and sustainable ecosystems that contribute to climate change

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adaptation and mitigation. A very popular approach is famer-managed natural regeneration (FMNR), which has a number of advantages over other approaches in the context of drylands. FMNR has been actively promoted in the Sahel for over four decades, spreading from Niger to the neighbouring Burkina Faso and Mali in the 1980s and currently to other regions in Africa and Asia. FMNR is farmer driven and creates multifunctional landscapes that offer multiple ecosystem services. At the adaptation level, FMNR restores the degraded ecosystem services such as the provision of goods to local communities facing shocks and creation of resilient production systems against extreme weather events. At the mitigation level, FMNR contributes to carbon sequestration in plant biomass and soils while reducing greenhouse gas emissions. The chapter concludes with two cases of FMNR illustrating the benefits to dryland communities.

Keywords Agroforestry · Aridity · Biodiversity · Ecosystem services · Food security · Income security · Land degradation · Landscape restoration

3.1 Introduction

Human activities have increased global temperatures 1 °C above pre-industrial levels (IPCC 2018), causing climate change, the most universal threat to mankind. In Africa, all regions have experienced mean temperatures and hot extremes above natural variability when compared to long-term average between 1850 and 1900 (IPCC 2021); a trend that is projected to continue with additional global warming (WMO 2019). Precipitation in the continent also shows geographical contrasts. Most regions are projected to experience decreases in mean precipitation, increases in heavy precipitation and pluvial flooding and increases in drying and agricultural and ecological droughts (IPCC 2021). There are also projected increase in mean wind speed, increase in fire weather conditions and increase in river flooding in few regions (IPCC 2021). These projections suggest that some regions will be warmer; some will get above normal rainfall, while others will be exposed to more frequent droughts. Raising temperatures, changing precipitation patterns and extreme weather already threaten human health and safety, food and water security and socio-economic development in Africa (WMO 2019).

Africa contributes the least amount of greenhouse gas (GHG) emissions, although it has emerged as the most vulnerable region in the world (IPCC 2021). This vulnerability has been attributed to more severe extreme events in the region, dependence on weather-sensitive sectors such as agriculture, herding and fishing, and limited capacities to cope and adapt to impacts of climate change. Agriculture in Africa, for example is almost entirely rainfed, with 6% of the continent's farmland (4% in SSA) irrigated (Svendsen et al. 2009). Food insecurity is expected to be most severe impact of climate change due to rising dryness and the reduced adaptive capacity of smallholder farmers. Poor communities are the worst affected because they lack the resources to afford goods and services necessity to cushion them and recover from effects of climate change. Incidentally, an overwhelming majority of the extreme poor in Africa live in rural areas and depend on agriculture for their livelihoods (Olinto et al. 2013). The plight of rural communities has recently been worsened by the COVID-19 pandemic.

Climate change adaptation and mitigation are two complementary pathways to tackle climate change. Climate adaptation refers to actions undertaken to manage effects of climate change by reducing vulnerability and exposure to its detrimental influences and taking advantage of any potential benefits (IPCC 2018). On the contrary, climate change mitigation refers to actions that limit or reduce the magnitude or rate of anthropogenic climate change over the long term (IPCC 2018). Nature-based solutions, when executed correctly, can deliver several benefits, including for climate change adaptation and mitigation (Griscom Griscom et al. 2017; IPCC 2018). Nature-based solutions can provide over 66% of the cost-effective climate mitigation needed to stabilize warming to below 2 °C by 2030 (Griscom Griscom et al. 2017). Tree-based production systems are an example of nature-based solutions with great potential to reduce vulnerability and increase the resilience of households in Africa (Place et al. 2016). This chapter explores the contribution of trees regenerated by farmers to climate change adaptation and mitigation.

3.2 Africa's Drylands

3.2.1 Ecology and Community Livelihood of Africa's Dryland

Drylands are areas with an aridity index (AI) below 0.65, and are classified into hyper-arid (AI: <0.03), arid (AI: 0.03–0.20), semi-arid (AI: 0.20–0.50) and dry sub-humid (0.50–0.65) (UNEP 1997). Aridity index measures the level of dryness of a place and is calculated as the ratio of mean annual precipitation to potential evapotranspiration. Drylands experience annual potential evaporation and plant transpiration that surpasses yearly precipitation. The hyper-arid areas are largely natural deserts and are uninhabited except for a few oases that are sparsely populated; arid zones are exclusively under extensive grazing; semi-arid zones are characterized by rainfed cropping in wetter areas and pastoral farming in drier areas; the dry sub-humid zones are forests and wooded with extensive farming (Safriel et al. 2005; Pricope et al. 2013; Davies et al. 2016). The people and species in drylands are adapted to the unique conditions of water scarcity and unreliable and erratic rainfall.

Drylands are characterized by water scarcity due to low rainfall and excessive water loss through evaporation and transpiration (Davies et al. 2016). Some dryland regions (e.g. in equatorial Africa) may receive on average more than 1000 mm/year (Davis et al. 2017). However, high mean temperatures and prolonged dry season exacerbate the rate of evapotranspiration, causing aridity. Drylands are likewise characterized by variable climatic conditions (Safriel et al. 2005), for example variable rainfall, frequent droughts that are nowadays severe and last longer, strong winds and wildfires (MEA 2005). Some dryland areas experience extreme rainfall events that cause flooding; others experience severe droughts. This causes widespread poor harvests and crop failure on one hand, and damage to crops, livestock and infrastructure and displacement of people on the other hand. According to the Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2018), the intensity and frequency of droughts and floods in Africa are predicted to increase, leading to longer and more severe fire seasons in the region (IPCC 2018). This will shatter livelihoods, cause displacement of communities and migration of pastoralists, and result in conflicts over natural resources (IPCC 2018).

It is important to note that already, one-third of the world's drylands are located in Africa (Mirzabaev Mirzabaev et al. 2019). Africa's drylands cover 43% of the continent, account for about 75% of the agricultural land and support close to half of the continent's population (Cervigni and Morris 2016). The size of Africa's drylands will continue to change depending on the population size, the type of economic activities and technologies adopted in the future. By 2050, the population of some countries in Africa is expected to double their current size (United Nations 2017). The number of people living in the drylands of east and west Africa is expected to increase by 65–80% during the same period (Cervigni and Morris 2016). At the same time, the area classified as dryland is expected to increase greatly. High population and increased interest in land in Africa will put additional pressure on the continent's natural resource base.

Dryland communities rely on natural resources for their livelihoods. The majority are subsistence farmers who eke out a living from farming or herding. The potential of agriculture to support livelihoods in drylands is however waning (Safriel et al. 2005). Agricultural productivity in drylands is limited by natural constraints (precipitation and temperature variability), and low input management. Drought is the most challenging climate hazard and a threat to food security in Africa in general. For instance, drought is a leading cause of crop failures in drylands of Africa, putting millions of the population at risk of hunger, malnutrition and starvation. For smallholder farmers, crop failure means food and nutrition insecurity and lack of income to buy food and agricultural inputs. Dryland agriculture is also affected by inherent low soil fertility, salinity, wind erosion, frequent fires and agricultural pests (Safriel et al. 2005). These factors cause food shortages and increase the prices of food, with dire impacts on the resource-poor farmer.

3.2.2 Drivers of Dryland Degradation in Africa

Land degradation is defined as the decline or loss of the biological or economic productivity of land (MEA 2005). About two-thirds of agricultural land in Africa is degraded (ELD Initiative and UNEP 2015). Much of this is found in drylands (MEA 2005). The degradation of drylands is partly due to natural factors, but it is accelerated by human activities. Droughts, bush fires, overgrazing, agricultural expansion and over-exploitation of natural resources are some of the drivers of land degradation in drylands in Africa (Dimobe et al. 2015). These factors lead to the replacement of native vegetation with crops, exposure of soil making it vulnerable to erosion and widespread use of fertilizers that modify the soil physical and chemical properties. Land degradation in drylands can lead to desertification (Darkoh 1998), defined as land degradation in arid, semi-arid and dry sub-humid areas (Mirzabaev Mirzabaev et al. 2019). Approximately one-third of Africa is affected by desertification (Darkoh 1998; Mirzabaev Mirzabaev et al. 2019). Among those affected are the poor and marginalized communities in drylands whose survival is already at risk.

There is a link between desertification and climate change. Drylands are prone to desertification because of limited primary productivity and sluggish recovery after disturbance (MEA 2005; Mirzabaev Mirzabaev et al. 2019). Desertification reduces vegetation cover, increases sandstorms and can increase greenhouse gas (GHG) emissions. This undermines climate change mitigation efforts by reducing carbon sequestration and increasing the proportion of solar radiation that is reflected by a land surface (albedo) (MEA 2005). Extreme weather events (e.g. floods, droughts) and reduced soil conservation cause soil erosion, a land degradation process that is common in drylands. At the same time, erosion contributes to climate change through reduced carbon storage and increased carbon dioxide (CO_2) emission. Loss of nutrients and soil moisture due to soil erosion affects biodiversity and can reduce vegetation cover (Darkoh 1998). Change in vegetation cover is one of the easy-to-detect and commonly used environmental indicator of dryland degradation (Yirdaw et al. 2017).

Much of land degradation in Africa is driven by the need to survive, with inappropriate land use and management, poverty and rapidly growing population as the leading causes. Research has suggested existence of a vicious cycle in which land degradation leads to loss of livelihoods, which results to poverty. Poverty, food insecurity and lack of clear tenure rights over natural resources impel people to overexploit dryland natural resources. Farmers and pastoralists use low input management (e.g. residue removal without fertilization) that progressively reduces soil fertility and vegetation. They cultivate marginal lands and use primeval practices that hardly increase yields. Due to increased population, some traditional practices such as fallowing that allowed land to regenerate have been abandoned in many parts of Africa. Clearing woody vegetation to allow grass for livestock to grow or to maximize production in tree-less systems is another factor of degradation. In absence of alternative sources of energy, dryland communities rely mainly on woodfuel for cooking, which contribute to the clearing of woody vegetation. For instance, widespread harvesting of Vitellaria or shea tree (*Vitellaria paradoxa*) and excessive pruning and limited regeneration of Faidherbia (*Faidherbia albida*) threaten the existence of the two species in the Sahel. Grazing is also widespread in drylands, and has been identified as one of the main drivers of land degradation in drylands (Dimobe et al. 2015; ELD Initiative and UNEP 2015). Most pastoralists overstock, and always try to feed many animals on a limited supply of forage. Hotspots of vegetation degradation in pastoral regions have already been identified in East Africa (Pricope et al. 2013). Through defoliation and trampling, overgrazing reduces vegetation cover and compacts the soil, exposing it to erosion. Degradation of the natural resources base, in turn, leads to poverty which is aggravated by climate change. Restoring degraded lands is needed to boost soil productivity and improve the livelihoods of drylands communities.

3.2.3 Restoration of Degraded Drylands

Restoration refers to intentional activities that initiates or accelerates the recovery of an ecosystem from a degraded state (IPBES 2018). In this chapter, restoration refers to the intentional addition and improvement of vegetation cover in degraded landscapes. Ecological restoration entails aiding a degraded ecosystem to recover plant vegetation. The recovery can be increased by using a range of approaches from relatively passive ones to more active actions. The passive approaches include assisted natural regeneration through enclosures in rotational grazing; examples of active measures are enrichment planting, mixed-species planting, framework species, maximum diversity and use of nurse trees (Yirdaw et al. 2017). Restoration is often applied to abandoned or natural systems to bring them back to their natural state, but it can also be applied to landscapes that are under human use to rehabilitate and improve them (IPBES 2018). Restoration of degraded drylands may include one or a combination of the following actions: reestablishment of vegetation (e.g. planting or assisted natural regeneration), protection (e.g. from fire, grazing, erosion, termites and weeds) and management actions (e.g. pruning and thinning). The strategy employed depends on the type, extent and degree of degradation (Safriel et al. 2005). Protection and management actions are applied where degradation is low. Planting on the other hand is undertaken where there is severe degradation (Yirdaw et al. 2017). Planting involves the selection of species, production of planting material, preparation of a site for planting and administration of silvicultural practices. Restoration has been recognized as critical in reversing land degradation, increasing productivity and enhancing resilience to climate change (MEA 2005; Mirzabaev Mirzabaev et al. 2019).

Restoration of degraded landscapes with increased tree cover contributes to various climate initiatives. Under the Bonn Challenge, 31 Africa countries have committed to restore 128 million hectares of degraded lands by 2030. Africa accounted for close to 75% of the 2020 global forest restoration target under the Bonn Challenge. Under the African Forest Landscape Restoration Initiative (AFR100), 27 countries have pledged to restore 100 million hectares of degraded land by 2030. Both the Bonn Challenge and the AFR100 contribute to parties' pledges to tackle climate change, biodiversity and land degradation. Globally, realizing the Bonn Challenge can jointly sequester at least 0.6 Gt of CO_2 annually, attaining at least 1.6 Gt/year in 2030. At the national level, countries can contribute to the mitigation goal through their intended nationally determined contributions (NDCs). Agroforestry is one of the means that some countries plan to use to achieve restoration targets and to fulfil their NDC targets (Duguma et al. 2017; Rosenstock et al. 2019). For example, 71% of the countries from Africa have proposed agroforestry in their NDCs (Rosenstock et al. 2019). Agroforestry can contribute to NDCs directly by carbon sequestration and substitution of inorganic fertilizer, and indirectly by reducing deforestation and forest degradation via provision of wood and other tree products that are normally obtained from the forests.

Africa has the largest land area with opportunities for landscape restoration (Minnemeyer et al. 2011). A global analysis by Zomer et al. (2014) found that the proportion of agricultural land with trees in SSA had increased by 1.85% between 2000 and 2010, and that there was still potential for increasing trees on agricultural land, particularly in low potential areas and unproductive lands. By mapping population density and land use, Minnemeyer et al. (2011) and Laestadius et al. (2011) identified two landscapes where restoration opportunities for agroforestry are more likely to be found: (1) areas with moderate human pressure (10–100 people/km^2), and (2) areas with intensive human pressure (more than 100 people/km^2). Most of the land available for restoration (~730 million ha) supports a mosaic-kind restoration in zones with moderate human pressure, where trees can be combined with crops under agroforestry (Laestadius et al. 2011). These includes agroforestry parklands, planted fallows, woodlots and hedgerows intercropping, contour planting and buffer strips (Laestadius et al. 2011). On the other hand, areas with high population density or intensively managed for crop production can have trees planted in targeted areas, for example along contour lines in sloping land to control erosion, along boundaries or within the homestead (Minnemeyer et al. 2011).

Restoration of degraded drylands is constrained by harsh climatic conditions, degraded soils and limited resources among rural communities. First, the dryland conditions make the narrow range of species adapted to harsh conditions vulnerable to disturbance, and slows down the recovery of species after the disturbances (MEA 2005; Safriel et al. 2005). Second, the survival of seedlings in drylands is limited by water scarcity, which is worsened by drought and poor soils. Overcoming drought at the seedling stage is therefore critical for the restoration of drylands. This can be achieved by increasing the water-holding capacity of the soil to extend water supply to seedlings during establishment. Rainwater harvesting techniques (e.g. Zaï) or using organic amendments (or mulch) can reduce evaporation and increase water availability to seedlings (Kuyah et al. 2021). Despite these constraints, there are many opportunities for the restoration of dryland areas in Africa. This is because (1) much of the drylands are already degraded, (2) a large proportion is undergoing degradation and (3) expansive areas are considered of low agricultural productivity and their productivity can be improved by integration of woody vegetation.

Sustainable land management (SLM) interventions have been championed as critical for restoration of degraded landscapes in Africa. Restoration efforts in rangelands target to re-establish grasses, herbs and to generate a new ground cover (Öborn et al. 2022), while, the efforts in croplands aim to restore productivity of farms. Several SLM interventions have been used to achieve restoration goals in drylands including planting or regenerating woody vegetation, use of enclosures (fencing) or exclosures (Tougiani et al. 2009; Sawadogo 2011). There are also indirect measures aimed at reducing degradation such as using efficient stoves and improved pyrolysis of biomass during production of charcoal or biochar. The option taken for restoration depends on the type of land use (rangeland, cropland, forested land, etc.). Tree-based production systems are recommended as the most important interventions for the restoration of Africa's drylands (Cervigni and Morris 2016). Using trees to restore degraded lands can enhance ecosystem services that regulate crop and livestock productivity and provide additional resources that communities can use to cope with climate shocks. Restoration with trees has also been recognized as the most effective strategy for climate change mitigation (Bastin et al. 2019).

3.2.4 Ecosystem Services Through Restoration of Drylands

Ecosystem services (broadly defined as benefits that humans derive from nature) in drylands hinge on the condition of rangelands and croplands as well as other minor land use types. Rangelands and croplands accounts for 90% of dryland areas while forests and woodlands jointly account for 10% of the drylands (Safriel et al. 2005). Drylands support the livelihoods of communities through agropastoral, agrisilvicultural and silvopastoral activities. Agroforestry systems in rangelands and croplands are mainly silvopastoral systems, homegardens, windbreaks and shelterbelts, multipurpose trees on croplands and extensive tree intercropping, commonly referred to as parklands (Nair et al. 2021). These land use types provide a range of ecosystem services that are critical for the well-being of dryland communities.

3.2.4.1 Provisioning Services

The main provisioning ecosystem services in drylands are food, medicine, fodder, fibre, fuelwood and biochemicals (Safriel et al. 2005). Dryland ecosystems support food production from crops and livestock; provision of tree foods such as fruits and leafy vegetables; and regulating ecosystem services necessary for production of food. Drylands are the leading producers of high-quality grains from cereals, e.g. sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*) and wheat (*Triticum aestivum*); and legumes, e.g. cowpea (*Vigna unguiculata*), groundnuts (*Arachis hypogaea*) and pigeon pea (*Cajanus cajan*) and bambara groundnut (*Vigna subterranea*). Wild varieties of these crops with origin in drylands are used to provide genetic plant material for breeding crops that are drought tolerant. Drylands are characterized by low production per unit area and rapid expansion of production area. Farmers are always expanding the area under production to meet the increasing demand for food, fodder and fibre. For example, between 1984 and 2013, bare soils and agricultural lands in Burkina Faso increased by 18.8% and 89.7%, respectively; while woodland, gallery forest, tree savannahs, shrub savannahs and water bodies decreased by 18.8%, 19.4%, 4.8%, 45.2% and 31.2% during the same period (Dimobe et al. 2015). The pressure to increase provisioning ecosystem services is a major cause of land degradation in drylands.

Drylands support livestock production under rangelands or agropastoral systems. Livestock production in drylands also involve silvopastoral systems where animals freely roam and graze under natural stands of trees or shrubs or scattered trees in croplands (Nair et al. 2021). There are also cases where animals are stall-fed with forage from fodder crops, trees and shrubs, for example cut-and-carry from fodder banks. Numerous trees and shrubs are used for fodder in Africa. Similarly, a large variety of animals are kept for meat, milk, wool and leather products. The animals constitute a major source of income and proteins in the diet of dryland communities. They also help in maintaining soil fertility. However, grazing loads of animals reduces vegetation cover, tramples the soil and causes soil compaction. This trio decreases infiltration of rainwater, increases runoff and accelerate soil erosion. The degradation of drylands has reduced grazing potential and livestock productivity in dryland areas of Africa (Pricope et al. 2013).

Trees and shrubs in drylands generate multiple provisioning ecosystem services. A recent review found abundant literature on the contribution of woody vegetation to food security and nutritional diversity, material assets, income and energy (Sinare and Gordon 2015). Fruits and vegetables are an important source of food in drylands. Trees and shrubs that produce fruit or nuts are common in homegardens and other agroforestry systems where they are planted alone, along boundaries or integrated with arable crops (Nair et al. 2021). Tree and shrubs also provide timber, fuelwood and other wood products. Wood is commonly produced from windbreaks, trees planted along boundaries, homegardens or parklands (Kuyah et al. 2020). Some tree products are obtained from the wild, although this is declining due to unsustainable exploitation and restrictive laws. Domestication of indigenous species is one of the ways of increasing the provisioning of goods that are no longer obtainable from the wild (Jamnadass et al. 2013). A list of trees and shrubs that are being domesticated for various products is found in Nair et al. (2021). Production of wood and tree foods on farms can reduce pressure on forests and woodlands.

Dryland ecosystems provide natural gums and resins, spices and condiments, wild honey and bees wax and essential oils that are used in a variety of ways. Examples of dryland species that produce gum and resin include *Senegalia senegal*, *Vachellia seyal*, *Senegalia polyacantha*, *Boswellia dalzielii*, *Boswellia papyrifera*, *Boswellia microphylla*, *Boswellia ogadensis*, *Boswellia pirrotae*, *Commiphora myrrha*., *Commiphora africa* and *Commiphora habessinica*. The gums and resins are an important source of income and off-farm employment. Some of the products are used as food additives; as thickening, stabilizing, emulsifying and suspending agents in beverages, as adhesives or traditional medicines. Provisioning ecosystem services depend on primary productivity, a key supporting ecosystem service.

Water Purification and Regulation

Low rainfall and high evapotranspiration being the main limiting factor, water regulation is a major dryland ecosystem service with an influence on water provision and primary production. Water purification is also important for agricultural and domestic use in rural and urban cities found in dryland areas (Davies et al. 2016). Oases support water regulation function in arid and super-arid zones and have been carefully managed to sustain this function over centuries. The semi-arid and dry sub-humid zones have watersheds that supply freshwater, although the resource is rationed and supply is irregular. Watersheds in degraded drylands are highly vulnerable to erosion and flash floods. Vegetation in these watersheds regulates water flows, mitigates the risk of floods and erosion, and contributes to rainfall production through changes in albedo and evapotranspiration. One of the ways vegetation modulates water is by intercepting rain, holding the water for a while, and releasing it gradually. In the parklands of western Senegal, *Cordyla pinnata* trees intercepted 22% of the total annual precipitation (Samba et al. 2001). Reduced plant cover thus disrupts water regulation.

The collection and management of rainwater or floodwater is a common practice used to increase water availability for domestic and agriculture use in drylands (Larwanou and Saadou 2011; Davies et al. 2016). Water harvesting practices can improve crop yields and positively impact other ecosystems services by increasing local biodiversity and improving soil conditions. Common water harvesting techniques used to increase water availability in drylands are floodwater harvesting and micro- or macro-catchments (Sawadogo 2011). In floodwater harvesting, small bunds are built with stones or earth to divert runoff or floodwater towards cultivated fields, or to intercept floodwater from intermittent streams to increase infiltration into the soil or to divert some of the floodwater to nearby fields for irrigation or other uses (Sawadogo 2011). This water would have been lost to evaporation or uncontrolled runoff. Floodwater harvesting practices recharge aquifers and control flood and wind erosion. Other water harvesting techniques include macro-catchments such as sand dams and micro-catchments such as Zaï. Zaï pits are common in the drylands of West Africa, and recently in East Africa. Farmers dig small pits measuring 60 cm long, 60 cm wide and 30 cm deep or different dimensions depending on the crop to be planted (Zougmoré et al. 2014). Zaï pits are used to collect water and sediments, concentrate soil fertility around the crop root zone and to increase water infiltration for crops and recently for trees.

Dryland vegetation affects hydrological functions that modulate the storage and availability of water in the system. Specifically, dryland vegetation improves soil water storage through increased infiltration rate and reduced runoff (Rhoades 1995). Increased infiltration reduces the amount of rainwater available for runoff or overland flow. The effect of dryland vegetation on water regulation has mostly been studied on cropland, with a focus on changes in soil water content in the topsoil and the rate of infiltration (Kuyah et al. 2016, 2019). The majority of these studies have been conducted at plot level (Sinare and Gordon 2015; Kuyah et al. 2016). A meta-analysis based on studies from semi-arid SSA found a positive overall effect of woody vegetation on water regulation (Kuyah et al. 2019). Agroforestry practices reduced runoff and soil loss and improved infiltration rates and soil moisture content (Kuyah et al. 2019). The response is however moderated by seasonal variations in rainfall (Sinare and Gordon 2015). For example, Baobab (*Adansonia digitata*) and *Balanites aegyptiaca*, show positive effects during the rainy season and no effect during the dry season; *B. aegyptiaca* shows negative effects towards the start of the dry season (Sinare and Gordon 2015). Plot level studies in the West Africa have shown increased infiltration under Parkia (*Parkia biglobosa*), Baobab, *Guiera senegalensis* and *Piliostigma reticulatum*, compared to open areas (Kizito et al. 2006; Sanou et al. 2010), and reduced evaporation and runoff under fields with *G. senegalensis* and *P. reticulatum* (Kizito et al. 2007).

Dryland vegetation contributes to the improvement of water quality. Vegetative buffer strips and riparian buffers reduce the amount of nutrient and sediments carried from the landscape into water bodies. The vegetation forms barriers that trap and remove pollutants from overland flow, and can also act indirectly by reducing the rate of soil erosion. Some plants absorb certain minerals, reducing pollutants. Tree and shrubs can trap and utilize nutrients from deeper soil horizons or during off season (Nair et al. 2021). This can enhance nutrient storage in the plant–soil system, and reduce the amount of nutrients that are moved via runoff or leaching.

Climate Regulation

Drylands regulate climate at local scale through vegetation cover and at global scale through carbon sequestration. At the local scale, changes in vegetation cover alter albedo with consequences on rainfall. An increase in albedo leads to a decrease in surface temperature while a decrease in albedo leads to a rise in surface temperature (Charney et al. 1975). Degraded drylands have reduced plant cover, a high albedo, high surface temperature and receive low rainfall (Charney et al. 1975). Dryland vegetation also modifies the local climate by regulating dust storms. Low plant cover exposes the surface and accelerates formation of dust storms. Dust storms increase albedo and lead to air problems locally and outlying regions. Desertification increases dust storms by diminution of plant cover and drying the soil surface (Darkoh 1998). Dryland ecosystems also influence local climate by the effect of vegetation on evapotranspiration rates. Reduced vegetation cover decreases shade, leading to high surface temperature and low soil moisture and reduced evaporation. A decline in evaporation has been linked to a decrease in rainfall production (Charney et al. 1975). A reduction in plant cover in the Sahel is one of the causes of reduced rainfall and the drought in the 1970s and 1980s.

Drylands play an important role in the global carbon cycle. Dryland ecosystems sequester carbon, regulating atmospheric CO_2. Through photosynthesis, carbon in the atmosphere is fixed into plant biomass, part of which is transferred to the soil when the remains of roots and residues decompose and form humus or when live roots release exudates via rhizodeposition. Some of the carbon is released back to the atmosphere through root respiration and microbial decomposition of organic matter.

Drylands have varying amounts of carbon stocks in above- and belowground biomass, ranging from very low in arid zones to relatively high in wetter dry sub-humid regions. For example, aboveground carbon density in shrub savannah and gallery forests in Burkina Faso is 2.9 ± 0.4 and 57.7 ± 3.9 Mg C ha^{-1}, respectively (Dimobe et al. 2019); and between 2.3 and 8.9 Mg C ha^{-1} in miombo woodlands in Malawi (Kuyah et al. 2014). In Ségou, Mali, carbon sequestration potential (above- and belowground) in major agroforestry systems is 0.29, 0.59 and 1.09 Mg C ha^{-1} $year^{-1}$ in 7.5-year fodder bank, 8-year live fence and 35-year parklands (Takimoto et al. 2008, 2009); 5.85 Mg C ha^{-1} $year^{-1}$ in 26-year cocoa agroforests (Duguma et al. 2001) and 6.31 Mg C ha^{-1} $year^{-1}$ in 13-year shaded agroforests (Dossa et al. 2008). The potential of carbon sequestration in drylands is large given their large spatial extent. However, climate change and human activities is projected to decrease vegetation production and biomass carbon stocks in drylands.

Globally, drylands are estimated to store about 27% of the total soil organic carbon (SOC) stocks. They also have greater potential for carbon sequestration as the soils are not yet close to saturation. However, the absolute SOC content in drylands is low (<1% SOC), largely due to degradation. Drylands can act as sinks or sources of carbon depending on the inputs or outputs of carbon in the pool. Dryland conditions affect their capacity to sequester carbon. Photosynthesis in drylands is limited by water availability, reducing the amount of organic matter available for input into the soil. Lack of soil moisture also lowers the rate at which organic matter is changed to humus. On the contrary, drylands rapidly lose the little carbon when disturbed, for example through bush fires, over-cultivation, overgrazing or overharvesting of dryland products (Dimobe et al. 2015). The warm climate also accelerates SOC turnover in dryland. A key to increasing carbons sequestration in drylands is to promote conditions that allow accumulation of organic matter and that increase biodiversity.

Soil Conservation

Dryland vegetation contributes to soil conservation by controlling wind and water erosion and by improving soil fertility. Soil erosion is a major threat in drylands and the leading land degradation process. Vegetation in drylands protects the soil from the effects of wind (wind erosion), rain (water erosion) and the sun (excessive heat). Wind erosion occurs when a strong wind blows over bare land or land with sparse vegetation and where the soil is dry or sandy, for example in the Sahel. Trees provide mechanical barriers that reduce wind erosion. Windbreaks and shelterbelts are a specific agroforestry practice in drylands that function to conserve soil and reduce damage to crops, livestock and property by reducing wind speed (Kuyah et al. 2017, 2019; Nair et al. 2021). For example, *Euphorbia tirucalli* is widely found along boundaries of crop fields and settlements drylands of Kenya and Tanzania; Casuarina are used in canals and irrigated fields in Egypt; while multipurpose shelterbelt trees are common in the Sahel (Nair et al. 2021). Dryland vegetation control water erosion by checking the speed and volume of runoff through the formation of physical barriers. The vegetation intercepts rainfall, reducing the impacts of raindrops on soil particles (Samba et al. 2001); they also stabilize the soil by their roots. Contour bunds with vegetation and hedgerows are the most common practices of controlling soil erosion in wet semi-arid areas in Sub-Saharan Africa (Kuyah et al. 2019). Controlling soil erosion can increase soil fertility, improve recharge of ground water, and reduce the build-up of sediments in dams and waterways.

When well-managed, dryland ecosystems improve soils by providing organic inputs into the soil, reducing losses of organic matter and nutrients and improving soil physical properties. Plants add organic matter via nitrogen and carbon fixation and transfer of these compounds to the soil. The amount of nitrogen fixed annually in drylands is usually low, as it peaks when conditions are conducive and reduces when temperatures are high and soil moisture is low. Much of the nitrogen fixation in dryland ecosystems is facilitated by cyanobacteria present in biological soil crusts (e.g. *Nostoc*), heterotrophic bacteria found in the root zone of plants (e.g. *Azotobacter*), and bacteria that form an association with leguminous plants (e.g. *Rhizobium*). The main nitrogen-fixing plant species in drylands include species of *Acacia*, *Prosopis*, *Pterocarpus* and *Pericopsis*. Trees such as *Faidherbia*, *Parkia* and *Vitellaria* also fix nitrogen in croplands and pasture. Other trees such as neem (*Azadirachta indica*), Baobab, *B. aegyptiaca* and *P. reticulatum* and shrub *G. senegalensis* contribute to soil conservation through addition of organic matter (Sinare and Gordon 2015). Organic matter improves soil structure, porosity and water retention capacity. Dryland vegetation reduces loss of organic matter and nutrients by promoting nutrient cycling and controlling erosion. They also trap and recycle nutrients which would otherwise be lost through leaching, and reduce the rate of organic matter decomposition by influencing the microclimate.

3.2.4.2 Cultural Services

Cultural ecosystem services are the non-material benefits that humans enjoy from nature. Drylands ecosystems support cultural identity and diversity, cultural heritage, recreation, indigenous knowledge systems, spiritual enrichment, aesthetic values and inspirational services (MEA 2005). The ecosystems in drylands play a significant function in defining the identity and diversity of dryland communities. Drylands are characterized by open, vast and attractive landscapes that serve as tourism destinations, and support recreational activities such as sport hunting, wildlife watching, hiking, camping and photography. The savannahs, dry forests and woodland ecosystems and coastal areas attract tourists. Drylands are home to leading national parks, world's heritage sites and other protected sites. They also host human-dominated landscapes that attract tourists. For example, the Chaaga homegarden in Tanzania is a popular ecotourism attraction (Nair et al. 2021). Drylands are also home to certain endemic species that people go to view, and sites considered to be culturally or spiritually important.

Trees play an important part in the cultural services of drylands, including ceremonies, traditions and rituals (Kuyah et al. 2016). The communities protect certain plant species for their assumed cultural values. For example, *Erythrina abyssinica*, a medically important indigenous and endangered plant locally known as *Omurembe*, is not used as firewood for cooking among the Banyore of western Kenya. The tree is also believed to have certain cultural benefits and therefore, protected wherever it grows, most naturally. In Burkina Faso, *Gardenia erubescens*, Baobab, Lengue (*Afzelia africana*), Karaya gum tree (*Sterculia setigera*), Pink Jacaranda (*Stereospermum kunthianum*) are used as totemic species. The wood of these species cannot be taken home as they are believed to bear magical/spiritual powers. Each species has a history that is well known by the elders of local communities. Hygienic species such as Ironwood (*Prosopis africana*) and Dry-zone cedar (*Pseudocedrela kotschyi*) are also found in drylands and are generally used in mouth cleaning as a toothpick. In West Africa, the gathering of shea butter from *Vitellaria* is associated with dancing and singing. Vitellaria and other trees enhance social networks by providing products that are shared or exchanged among members of the community. Cultural ecosystem services are more documented in forests than in agricultural landscapes (Kuyah et al. 2016). Among agroforestry practices, homegardens are well known for the array of cultural ecosystem services they provide in many cultures. Trees in compounds and markets serve as resting places, meeting places and for socialization.

3.3 Farmer-Managed Natural Regeneration

Farmer-managed natural regeneration (FMNR) is one of the tree-based practices implemented by farmers to restore degraded landscapes. It is currently recognized as the most successful, cost-effective, easy-to-replicate approach to landscape restoration in the drylands of Africa (Cervigni and Morris 2016; Rinaudo et al. 2019).

3.3.1 FMNR Is Farmer-Driven

FMNR is a type of agroforestry where farmers deliberately protect and manage naturally regenerating trees or shrubs in on cropland or other land use types. FMNR draws from coppicing and pollarding, the two management practices that are traditionally applied to trees on farms when managing re-growth from stumps or stems, respectively. In practice, farmers select, prune/thin and manage regrowth of stumps, roots and seedlings instead of removing them when clearing fields for planting (Tougiani et al. 2009; Rinaudo et al. 2019). Pruning and thinning reduce competition, provide firewood or fodder, train trees/shrubs to grow upright and stimulate biomass production (Nair et al. 2021). Selected sprouts are protected from grazing animals, fire and weeds. The sprouts are maintained by thinning emerging lower stems and pruning side branches during the growing period (Tougiani et al. 2009; Rinaudo et al. 2019). FMNR aims to add trees to agricultural land, which makes it different from other revegetation practices (e.g. community-managed natural regeneration, assisted natural regeneration, enrichment planting and managed exclosures) that involve the restoration of vegetation in the natural environment.

FMNR was initiated in response to a series of challenges that faced Sahelian countries for decades: extreme climate events, crop failures, food insecurity, severe fodder scarcities and frequent outbreaks of agricultural pests (Tougiani et al. 2009; Rinaudo 2012). The practice has been actively promoted in the Sahel for over four decades, spreading from Niger to the neighbouring Burkina Faso and Mali in the 80s and currently to other regions in Africa and Asia (Francis et al. 2015; Crawford et al. 2016). FMNR is currently practiced in 18 countries in Africa (Crawford et al. 2016). Several institutions have championed FMNR, including World Vision, World Agroforestry (ICRAF), World Resources Institute (WRI) and the Global Evergreening Alliance. Locally, governments and non-governmental organizations promote FMNR. Recent estimates indicate that FMNR has spread to about 7 million hectares in Niger and 21 million hectares in the Sahelian countries (Garrity and Bayala 2019).

FMNR is recommended as the most appropriate technology for landscape restoration in drylands, where the rate of survival of planted trees is very low (Rinaudo 2012; Crawford et al. 2016; Rinaudo et al. 2019). Low survival rates were a common phenomenon in the Sahel, where millions of dollars were invested in tree planting but forest cover was not increasing (Tougiani et al. 2009; Rinaudo 2012). On the contrary, trees managed under FMNR showed greater survival because re-sprouts have established root systems and arise from trees that are already adapted to local conditions. Sprouts also grow rapidly because they easily access (via the root system of the stump) soil moisture and nutrients and have reserves stored in the root system. Farmers prefer to revive and regenerate shrubs and trees because it is cheaper than planting new ones, where they incur costs related to production or purchase, transport and planting of the seedlings. Farmers regenerate some trees by feeding seed to livestock, which germinate better when they go through the gut.

3.3.2 FMNR Creates Multifunctional Landscapes

Farmers manage a variety of trees and shrub species under FMNR. In the Sahel, over 110 species are managed by farmers under FMNR (Kindt et al. 2008). Farmers normally regenerate species that are locally available, valuable and can sprout after cutting. Some of the species that naturally regenerate and are managed by farmers in the Sahel include *Faidherbia*, *Vitellaria*, *Parkia*, *B. aegyptiaca*, *Combretum glutinosum*, *P. reticulatum*, *Ziziphus mauritiana*, *G. senegalensis*, *Bauhinia rufescens*, Baobab, *S. senegal*, Tamarind (*Tamarindus indica*) and *P. africana*. These trees provide products such as fuelwood, fodder, fruits, condiments, gums, oils, poles, medicines, fencing and construction materials. Gum is used in many food items; shea butter is used in cooking and cosmetic industry; fruits and leaves from many species provide nutrients in the diets of many households; pods and twigs provide fodder during the dry season. The benefits of FMNR vary from place to place and depend on the type of species (Ndegwa et al. 2017; Moore et al. 2020; Kibru et al. 2021).

FMNR provides tangible benefits in the shortest time compared to planted seedlings. In the first year, farmers can get fodder, firewood and leafy material for green manure from pruned branches or thinned stems (Rinaudo et al. 2019). Availability of firewood and fodder is particularly important to women and boys, who have the responsibility of cooking and herding in many communities. Women across Africa spend up to 2.5 h collecting firewood (Crawford et al. 2016; Kuyah et al. 2020). FMNR reduces the time and effort required for women and girls to collect fuelwood, since they can now use the branches pruned from trees when preparing fields. This allows women and children to reallocate the time spared to other activities. FMNR farmers also have more grass and foliage available for livestock in the dry season, with a surplus for sale (Crawford et al. 2016). The trees may improve soil fertility, regulate microclimate and provide other benefits that improve crop yield. In the Sahel, areas with fewer trees get little cereal production, on average 200 kg ha^{-1} while those with high tree density get cereal yield up to 300 kg ha^{-1}. Communities where FMNR is practiced are reported to experience reduced conflict over natural resources, and increased social cohesion (Allen et al. 2009).

FMNR can be practiced in cropland (where nitrogen-fixing trees such as Faidherbia are dispersed on farm), woody thickets (where bushy multi-stemmed shrubs are pruned to allow grazing or fodder collection or reduce competition with trees), forest conservation (to regenerate degraded forests), in pasture (to manage trees, shrubs and grass for browsing and grazing), for water management (e.g. on hills and catchments to manage erosion, increase land stability and improve recharge of groundwater resources) and along fences (e.g. on farm boundaries) (Rinaudo et al. 2019). FMNR can be practised alone or integrated with other SLM practices such as Zaï, crop rotation etc. In Niger, farmers applying FMNR together with Zaï rehabilitated their fields with 126 trees/hectare compared to 103 trees/hectare in fields applying FMNR alone (Reij et al. 2009). In Burkina Faso, FMNR together with Zaï had a significant improvement in crop yield and increase in vegetative cover (Sawadogo 2011). FMNR also performed better when integrated with crop rotation in Ghana, where the net present value from enhanced crop production after 20 years was 295 Ghana cedis/acre without crop rotation and 786 cedis/acre with crop rotation (Westerberg et al. 2019). In the same study, annual net benefit per household was 559 cedis/farm/year without crop rotation and 649 cedis/farm/year with crop rotation (Westerberg et al. 2019). Integration of FMNR with other livelihood options provides alternative sources of income to meet immediate household needs, allowing communities to let trees grow to maturity.

3.4 Evidence for Climate Change Adaptation

FMNR provides goods and services that can aid communities to adjust to climate change and variability. This includes provision of products from woody vegetation for those facing climate threats, and creation of resilient crop and livestock production systems through more favourable microclimate, water regulation and soil improvement.

3.4.1 Provision of Products for Those Facing Climate-Related Threats

Tree products contribute to resilience by improving food and nutritional security and income. FMNR provides timber and non-timber products such as fruits, fodder, firewood, charcoal and medicines that are used by dryland communities facing climate threats. These products act as safety nets (in the short-term) and diversify livelihoods (in the long-term) among people experiencing climate threats (Pramova et al. 2012). For example, rural households turn to tree foods as part of their meals during the dry season or when crops fail (Jamnadass et al. 2013), and also sell trees or tree products for income (Miller et al. 2017).

3.4.1.1 Food and Nutritional Security

Fruit trees and vegetables in tree-based systems have been identified as critical for climate change adaptation in Africa. Their contribution to rural livelihoods has been documented (Miller et al. 2017) and fruit tree portfolios have also been developed for a range of species (Jamnadass et al. 2013; McMullin et al. 2019). Fruits and vegetables from FMNR diversify diets of many rural families, supplying the much-needed vitamins and micronutrients that are often lacking in energy-dense foods. For example, the fruits of baobab can be eaten raw or otherwise; dried pulp can be used as a flavour, a thickener or as a seasoning in traditional dishes. The baobab fruit contains high vitamins, minerals, and has several other health benefits (Jamnadass et al. 2013). Species such as *Strychnos spinosa*, *B. aegyptiaca*, *Z. mauritiana*, *Parkia* and *Vitellaria* provide edible leaves and fruits (Binam et al. 2015). A survey of on-farm fruit tree diversity and seasonality among 1200 households found a total of 31 different fruit tree species (including 9 indigenous species) in western Kenya and 51 species (including 27 indigenous species) in eastern Kenya (McMullin et al. 2019). Fruit tree calendars show that presence of trees on farms enhance the resilience of households to drought and irregular rainfall (Jamnadass et al. 2013; McMullin et al. 2019).

Fruits and other edible products contribute to household diets during the hunger period when most families deplete their stock of cereals. Rural households normally turn to tree-based foods during when they deplete their harvest or periods following crop failure (Jamnadass et al. 2013). Numerous studies provide evidence from field surveys and household interviews regarding the role of tree foods during droughts (Faye et al. 2010; Larwanou and Reij 2011; Larwanou and Saadou 2011; Sawadogo 2011). Anecdotal testimonies from farmers in Ghana suggest that FMNR farmers are more food secure relative to non-FMNR farmers because they can obtain fruits, nuts, and pods during the dry season, when they would otherwise face food shortage (Westerberg et al. 2019). Parkland trees such as *Vitellaria* and *Parkia* are treasured in west Africa because their products, which come in handy when crops fail or during the dry period (Garrity et al. 2010; Garrity and Bayala 2019). FMNR farmers are, therefore, well prepared to cope with unpredictable risks of climate change.

Increased livestock production is another way through which FMNR improves food and nutritional security in drylands. FMNR increases livestock production by increasing availability of fodder. The majority of FMNR trees provide fodder during the dry season, or improve production of grass or stover (crop residues) that serve as fodder. For example, Faidherbia produces high-quality pods and leaves for livestock browse. The deep tap roots of Faidherbia absorb minerals which are beyond the reach of other plant species and store them in their fruits/pods and leaves for future use. Trees such as *Vitellaria*, *Anogeissus leiocarpa* and *C. glutinosum* allow grass to grow beneath because of shade and moisture retention. Abundance fodder makes livestock keeping a rewarding enterprise as farmers keep more livestock that are well fed, and that produce more milk and meat. A study of households involved in an FMNR project in Humbo, Ethiopia, suggests that the number of main meals that include animal protein has increased following involvement in the project.

3.4.1.2 Income Diversification

Income plays an important role in reducing food insecurity and vulnerability of households in dryland conditions or during extreme weather events. FMNR can boost farmers' income through the sale of surplus crop yields, tree products, artefacts (tool handles, furniture) and livestock products (Larwanou et al. 2006; Tougiani et al. 2009; Binam et al. 2015; Crawford et al. 2016) or revenue from the sale of carbon credits (Brown et al. 2011). Farmers also raise trees as assets that can be sold in time of need (Crawford et al. 2016). In countries like Niger where fallows, bush and forest are gone, firewood produced on-farm generates substantial income for farmers. Some studies have associated FMNR with increased income from crops, particularly cereal and pulse in Ethiopia (Iiyama et al. 2017) and millets in Mali and Niger (Place et al. 2016). Households that produce surplus during years of sufficient rain sell it during lean periods. There is stronger evidence of FMNR contribution to household income in West Africa but anecdotal testimonies about impacts of FMNR on household income in East Africa.

Rural communities in Africa use tree products to diversify income (Kuyah et al. 2020). On average, a one-third of rural households with land smaller than 2 hectares grow trees, and the products from these trees account for about 17% of annual household income (Miller et al. 2017). Rural communities diversify livelihoods through the collection of fruits, fodder, medicines and spices, and production of timber and charcoal (Larwanou et al. 2006; Tougiani et al. 2009; Larwanou and Reij 2011). In Niger, women and girls collect baobab leaves which are sold to local markets; collection of shea nuts is common in Burkina Faso, while collection of Faidherbia pods is common in parklands. The sale of leaves of species such as *Pterocarpus erinaceus*, for animal feed is common in the cities of Burkina Faso and Mali during the dry season. In eastern Kenya (e.g. Makueni and Kitui counties), farmers maintain Melia (*Melia volkensii*) on croplands to provide timber, firewood, fodder and repellents. Melia and Baobabs are some of the trees one would find standing in eastern Kenya when rains fail and the land is stripped of vegetation. Farmers in Burkina Faso, Mali and Niger are known to regenerate and manage trees in order to reduce their sensitivity to climate change by harvesting fodder, fruits and other tree foods, or firewood which they sell or use for domestic purposes (Tougiani et al. 2009; Garrity et al. 2010; Sawadogo 2011). In Niger, farmers sell pods from Faidherbia for a higher price during drought years to make up for income forfeited from crops (case study 3.6.1). Trees are deep-rooted and therefore able to exploit nutrients and water at deeper soil profiles, which allows them to grow and provide products when crops are not able.

Collection and sale of tree products is a leading source of income for some rural households in Africa. Studies report income from tree products (timber, firewood or baobab leaves) under FMNR (Larwanou et al. 2006; Tougiani et al. 2009; Larwanou and Reij 2011; Sawadogo 2011). One of the largest surveys ($N = 1080$) in the Sahel found that individual households in Burkina Faso, Mali, Niger and Senegal can increase their income, on average, by 72USD if they practice FMNR continuously (Binam et al. 2015). In addition to improved income, these farmers reduce expenditure on food, fodder, firewood and construction material. A survey of 410 households in Maradi, Niger, found that FMNR increased annual household income by approximately 166 USD (18–24%) compared to non-adopters (Haglund et al. 2011). In the Ségou region of Mali, trees and shrubs in parklands contributed up to 650 USD/year in households where products from trees and shrubs were the main source of income (Faye et al. 2010). In East Africa, higher income (at mid-line compared to baseline) was realized from the sale of trees, tree products (charcoal, firewood, fruits, fodder, medicine), bee-keeping, and increased milk production (Crawford et al. 2016). By increasing the number of trees in the landscape, FMNR is likely to increase the quantity of tree products that are available for sale.

FMNR has potential for new income opportunities from carbon sequestration (Brown et al. 2011; Weston et al. 2015). Projects that sell carbon credits can benefit from emerging carbon markets, although this is still in infancy in Africa. The Humbo FMNR project in Ethiopia is one of the first projects to pilot income creation through carbon offset credits under the Clean Development Mechanism (Brown et al. 2011). The project provided an opportunity for communities that were affected by degradation to benefit from carbon markets and improved ecosystem services (Brown et al. 2011). A major problem with revenues from carbon markets is high transaction costs for projects requiring aggregations of several smallholder farmers. As currently designed, most market-based mechanisms do not match communities' needs for SLM activities. The approval process is also very slow and costly (Jindal et al. 2008). The advantage of FMNR regarding carbon sequestration is that it employs indigenous trees that provide multiple benefits with carbon as a co-benefit. In addition, FMNR does not disrupt livelihood systems of the locals since farmers do not need to change land use.

3.4.2 Creation of More Resilient Production Systems

Climate change affects dryland communities through its impact on agriculture and ecosystem services provided in natural or semi-natural habitats. Climate change affects agriculture through risks such as drought, floods and outbreaks of agricultural pests. In particular, farming and herding in drylands are threatened by rainfall variability and extreme temperatures. High temperatures increase the rate of respiration and shorten the growing period of crops, leading to poor yields or crop failure. High temperatures also cause production losses in livestock as it affects their normal body function and reduces the amount and quality of fodder available. Tree-based systems can ease vulnerability and raise the resilience of households in Africa's dryland (Cervigni and Morris 2016; Place et al. 2016). Trees in cropland and pasture fields can help maintain production under a variable climate and also protect crops and livestock against climate extremes.

3.4.2.1 Resilience Through Favourable Microclimate

FMNR has been identified among practices that increase farmers' resilience to high production risks in the Sahelian zone (Nkonya et al. 2016). Drylands of Africa are dotted with trees that provide shelter or shade to animals and shade for crops. Trees buffer crops against water stress associated with drought and dryland conditions. They reduce wind speed, increase humidity and reduce vapour pressure deficit (Bayala et al. 2014b). The trees also reduce solar radiation (Brenner et al. 1995) and evaporative demand by shading crops and the soil, minimizing evapotranspiration from crops and the soil. Trees moderate air and soil temperature; this reduces daily fluctuations and the time crops are subjected to extreme temperatures (Jonsson et al. 1999; Bayala et al. 2014a, b). These results in uninterrupted photosynthesis that lead to stable yields in fields with trees compared to those without trees. Shade has been explained as one of the factors responsible for improved yields under *Faidherbia*, *Parkia*, *Vitellaria*, Baobab and *B. aegyptiaca* in the Sahelian parklands (Jonsson et al. 1999; Sanou et al. 2010, 2012). A study in Senegal showed that the presence of *G. senegalensis* and *P. reticulatum* on fields decrease soil temperatures during daytime and increase soil temperatures during nighttime (Kizito et al. 2006). In Burkina Faso, pearl millet under parkland trees were less exposed to high temperatures compared to those in the open field (Jonsson et al. 1999). Shading by trees reduces evapotranspiration, and can improve soil moisture content.

Trees buffer crops from the effects of strong winds (Brenner et al. 1995). The importance of trees in regulating wind seed has been extensively studied in the Sahel, with mixed results under windbreaks (Brenner et al. 1995; Michels et al. 1998) but beneficial effects under parklands (Bayala et al. 2014b). Soils in the Sahel are more stable with trees (Michels et al. 1998; Allen et al. 2009; Garrity et al. 2010). In Bankass Mali, windbreaks improved crop production and quality by modifying the microclimate, reducing crop damage and reducing wind erosion (Allen et al. 2009). Farmers obtained improved millet harvests resulting from physical protection of soils in places where wind had previously buried millet shoots, leading to lower yields (Allen et al. 2009). Yield advantage of windbreaks occurs on the leeward side, with decreasing growth near the trees (Brenner et al. 1995). Sometimes the yield benefits can be sufficient to offset lower yields in areas near or occupied by the windbreak. However, yield benefit varies depending on weather and soil conditions, the type of crop and the type of tree species (Brenner et al. 1995; Michels et al. 1998). In Burkina Faso, Parkia and Vitellaria reduced wind speed in parklands with millet (Jonsson et al. 1999). Farmers in Niger suggest that trees such as Faidherbia improve the yield of sorghum and millet in their farms because of reduced wind speed (Tougiani et al. 2009).

3.4.2.2 Resilience Through Improved Soil Fertility

Trees make farming more resilient to drought by improving soil fertility, especially where the land is degraded. Trees build up soil organic carbon, which makes the soil resilient to drought and floods, and can stabilize crop yields. Several studies provide evidence from field surveys and household interviews regarding FMNR role in improved soil fertility. Farmers in Senegal, Ghana, Ethiopia reported an increase in soil fertility following the establishment of an FMNR project in their community (Weston et al. 2015; Crawford et al. 2016). An interview with 500 households in Mali revealed that farmers adopt FMNR because it increases soil fertility, in addition to provision of fuel, fruit and shade (Allen et al. 2009). In Ethiopia, farmers reported decreased on-farm soil erosion, less flooding and reduced siltation following establishment of FMNR and a subsequent increase in vegetation on the hillside (Brown et al. 2011). The farmers who identified soil fertility as a benefit of FMNR mentioned increased yield as evidence of improved soil fertility (Brown et al. 2011). In Malawi and Zambia, maize yields are better in farms with Faidherbia (Garrity et al. 2010), a nitrogen-fixing deciduous tree with reverse phenology (Roupsard et al. 1999). During the dry season, farmers who practiced conservation agriculture with Faidherbia trees obtained modest harvest while those who did not experience crop failure (Garrity et al. 2010). Anecdotal testimonies on FMNR by farmers and technicians in Niger and Burkina Faso suggest that trees such as Faidherbia improve sorghum and millet yields because of improved soil fertility (Tougiani et al. 2009; Garrity et al. 2010; Sawadogo 2011). Trees improve soil fertility through biological nitrogen fixation, nutrient cycling, increased abundance and activities of microorganisms and reduced loss of nutrients through erosion and leaching.

A review of key literature related to FMNR by Francis et al. (2015) found that FMNR has improved rural households' food security and resilience. FMNR improves household food security through increased availability of food that results from improved crop yield. Sorghum, maize, millets and vegetables are the most common crops associated with FMNR (in the Sahel). These crops are tolerant to heat and drought, and therefore dominate dryland farming systems. However, droughts and dry spells often lead to poor yield or crop failure. Experimental studies in Senegal showed that local millet varieties performed better (0.69 Mg ha^{-1}) under FMNR with 40 *P. reticulatum* trees/ ha compared to 0.41 Mg ha^{-1} plots without FMNR (Crawford et al. 2016). A recent study in Ghana showed that FMNR communities are considerably more food secure and climate-resilient (Westerberg et al. 2019). Around 2009, Nigerien farmers with FMNR realized an increase in crop yield of about 100kg/ha, creating an additional cereal production of 500,000 tons/ year that supported 1.7% of the (2.5 million) population of Niger (Reij et al. 2009). As a result of FMNR, crop harvests in Niger were increased, and the annual hunger or lean period reduced from 6 to 2 or 3 months in some communities (Reij et al. 2009). The effectiveness of FMNR increases with the number of trees per hectare and the size of trees (Box 3.1). Farmers with more trees or those who have mature trees receive significant benefits compared to those with few trees or young trees (Larwanou et al. 2006; Cervigni and Morris 2016; Westerberg et al. 2019). Household surveys also reveal that farmers reported increased crop yields as a benefit following the implementation of FMNR in Senegal, Ghana, and Ethiopia (Weston et al. 2015; Crawford et al. 2016). These benefits were however not measured but based on farmer perception.

Box 3.1 Increased Tree Cover and Greater Biodiversity

Evidence for climate change adaptation and mitigation can be inferred from increased tree cover and greater biodiversity under FMNR. FMNR increases tree cover in the landscape, evidenced by increased tree density and the area of land put under trees in different countries. Evidence of increased tree cover is found in project reports and peer-reviewed publications. In project review documents, respondents in household survey reported an increase in tree cover during the time of the project. Through FMNR, residents of Bankass Mali were able to achieve an average tree density of 277/hectare on their farms (Allen et al. 2009). The landscape was dominated by *C. glutinosum* (82%) while *G. senegalensis* and *B. aegyptiaca* jointly constitute 10% of the trees in Bankass (Allen et al. 2009). A study conducted by World Vision Senegal in the Kaffrine area showed that from 2008 to 2015 farmers have protected and managed their natural regeneration on 64,000 ha leading to an average on-farm tree densities of 4–37 trees/hectare (Reij et al. 2009). FMNR in the Maradi and

(continued)

Box 3.1 (continued)
Zinder regions of Niger led to an increase of tree densities and tree cover to ca. 4.8 million hectares of Faidherbia-dominated farmlands. These landscapes harbour populations of Faidherbia of up to 160 trees/hectare (Garrity et al. 2010). In Ethiopia, FMNR saw the restoration of 2728 ha that had been degraded through over-exploitation for wood, charcoal and fodder extraction (Brown et al. 2011).

FMNR contributes to restoration and conservation of plant and animal communities. Tree diversity is lower in farms of initial adopters of FMNR but higher in farmers where FMNR has been practised for a longer period. Mature trees attract birds or mammals that bring in more seed, and this will start to bring in new species and more diversity. Farmers in areas where FMNR has been mainstreamed into landscape management (e.g. Maradi, Niger) observed increased wildlife diversity (Francis et al. 2015). This has been attributed to the return of animals, birds and fauna that had disappeared from the region. Some birds and fauna that returned to the Sahel function to control insect pests, reducing the need for pesticides. In Ethiopia, farmers observed an increase in wildlife and birds in the neighbouring forest following adoption of FMNR (Brown et al. 2011). Increased tree species in FMNR includes the return of indigenous fruit trees. Greater biodiversity is critical for climate change adaptation and mitigation in drylands.

The effect of trees on crop yield is influenced by many factors, and show both positive and negative responses. Positive effects are attributed to favourable micro-climate and improved soil fertility in farms with trees as explained above. Negative results are attributed to competition between trees and crops, allelopathy and shading. A mid-term project review by World Vision has shown these variations, where majority of farmers in Kenya (44%) and Uganda (66%) reported an increase in crop yield following adoption of FMNR, 17% reported a decrease in both countries, while 38% in Kenya and 18% in Uganda reported no change in crop yield (Crawford et al. 2016). A different scenario was found in Tanzania, where 41% of the farmers reported a decrease, 36 reported no change and 24% reported an increase (Crawford et al. 2016); and in Rwanda where a comparable number of respondents reported increase (36%) and no change (37), while 27% reported a decrease in crop yield (Crawford et al. 2016). These variations suggest existence of trade-offs between provisioning and regulating ecosystem services in tree-based systems. For example, maximizing tree cover can increase water regulation, climate regulation and soil conservation, but leads to competition for light, water and nutrients, reducing crop yield. There is also a trade-off between creating resilience and crop yield in that trees cushion crops against climate but may decrease crop yields when climate related shocks are minimum or other disturbances are not present. Despite these trade-offs, trees are of greater value in dryland agriculture since it is characterized by high climate risks, has low soil fertility and agricultural inputs are low and cannot buffer against extreme weather event or land degradation.

3.5 Evidence for Climate Change Mitigation

Mitigation is a primary goal for global restoration efforts but a co-benefit for smallholder farmers. FMNR contributes to climate change mitigation by accumulating carbon in biomass and soils, and by reducing or avoiding GHG emissions on landscapes.

3.5.1 Carbon Sequestration in Biomass and Soils

FMNR is an ideal practice for long-term carbon sequestration because farmers can maintain trees and shrubs in the landscape while continuing with other farm enterprises. Adding trees in agricultural landscapes results in new carbon being sequestered. The amount of carbon sequestered in landscapes with trees is higher because of their greater capacity to sequester carbon when compared with other plant forms (Schoeneberger 2009). Similarly, the carbon content in trees is high, almost 50% of the dry matter. Much of the carbon in vegetation is held in aboveground parts, although branches contribute considerable amounts depending on tree architecture (Kuyah et al. 2014). Aboveground biomass of Faidherbia trees harvested in Malawi (average size of 55 cm DBH, 16 m height and 141 m^2 crown area) is about 689 kg/tree, with stem, branches and leaves representing 48%, 46%, and 6% of aboveground biomass, respectively. Aboveground biomass of *Mangifera indica* trees from Kenya (average size of 38 cm DBH, 9 m height and 61 m^2 crown area) is about 498 kg/tree, with stem, branches and leaves representing 30%, 61%, and 9% of aboveground biomass, respectively. In Burkina Faso, the aboveground biomass of *Vitellaria* trees with an average height of 7 m and a diameter of 17 cm is about 149 kg/tree, stem, branches, and leaves making up 21%, 74%, and 5%, respectively (Dimobe et al 2018). Climatic conditions, management and the type of species influence the size and number of trees in an area, the two major determinants of biomass carbon. Carbon sequestration can be increased when farmers protect and maintain trees on their farms.

Evidence for carbon sequestration in biomass is limited to studies conducted in agroforestry parklands in the Sahel, and a few experimental studies in agricultural landscapes in eastern and Southern Africa. These studies reveal that biomass carbon stored under FMNR is relatively large, and varies within and across locations; as influenced by environmental and climatic conditions and the architecture of tree species. Total carbon sequestered in biomass is about 1.4 Mg C ha^{-1} $year^{-1}$ in parklands and 7.5 Mg C ha^{-1} $year^{-1}$ in homegardens (Kim et al. 2016). Parklands sequester 1.1 and 0.3 Mg C ha^{-1} $year^{-1}$ in above and belowground biomass (Kim et al. 2016). Further evidence for climate mitigation under FMNR can be inferred from increased tree cover in farms under FMNR (Box 3.1).

Soil carbon is generally greater in farms with trees than those without trees (Nair et al. 2021). Bayala et al. (2020) found that regenerated trees increase soil carbon across the Sahel. The study considered 294 parkland fields in four countries (Burkina Faso, Mali, Niger and Senegal) and found enhanced soil total carbon under trees (Bayala et al. 2020). There is anecdotal evidence from project reviews that FMNR increases plant productivity (i.e. more biomass), which avails more organic residues into the soil (Crawford et al. 2016). The sloughing of roots, rhizodeposition and litterfall promote accumulation of carbon in the soil. Trees also affect soil carbon sequestration by modulating the rate of decomposition through their effect on microclimate and the abundance, variety and activity of microbes and other soil fauna. Deep-rooted trees and shrubs allow more carbon to be deposited in deeper soil layers, where the carbon is kept from disturbance and weather fluctuations (Nair et al. 2021). Build-up of soil carbon is determined by the type of species and the way the species are managed in the landscape.

A positive effect of trees on soil carbon is supported by a large body of evidence. SOC has been found to increase significantly under the canopy of trees and in plots with trees compared to open fields or tree-less plots. In Ségou, Mali, parklands with mature (>35 years) Faidherbia and Vitellaria trees had 33 Mg C ha^{-1}, live fences with *Vachellia nilotica*, *S. senegal*, *B. rufescens*, *Lawsonia inermis* and *Z. mauritiana* had 24 Mg C ha^{-1}, while fodder banks with *Gliricidia sepium*, *Pterocarpus lucens* and *P. erinaceus* had 33.4 Mg C ha^{-1} (Takimoto et al. 2009). The estimates are based on 54 soil samples from parklands, 27 soil samples from fences and 18 soil samples from fodder banks, all from 0 to 100 cm depth (Takimoto et al. 2009). In Southwestern Togo, 13-year shaded coffee including *Coffea canephora* var. *robusta* and *Albizia adianthifolia* had 97.3 Mg C ha^{-1} at 0 to 40 cm depth (Dossa et al. 2008). In Malawi, SOC concentration was 2.5% under canopies of large (mean canopy radius = 12 m) Faidherbia trees and 2.2% in the open fields, but 2.3% under canopies of small trees (mean canopy radius = 3 m) and 2.7% in the open fields (Rhoades 1995). In Ethiopian Vertisols, soil organic matter under Faidherbia was 69–107% higher than in the open (Kamara and Haque 1992). High soil organic matter and improved microclimate under trees enhance activities of soil microorganisms and other processes and soil physical properties that lead to the accumulation of carbon stocks. In addition to carbon inputs, trees enhance soil carbon storage by reducing losses of carbon due to soil erosion, leaching or the release of CO_2 from microbial respiration. Reduced disturbance (minimum tillage in areas occupied by trees), soil cover and higher diversity of plant species in FMNR can reduce carbon losses and increase the stability of SOC stocks.

3.5.2 Avoiding or Reducing GHG Emissions

FMNR can reduce emissions of nitrous oxide (N_2O), methane (CH_4) or CO_2. Agricultural landscapes with trees release fewer N_2O than those without tree (Kim et al. 2016). The trees reduce N_2O emissions by lowering the amount of nitrogen (N) fertilizer applied, or by taking up excess N. Trees on farm eliminate N application on the part of the farm occupied by trees, and can reduce the amount of N-fertilizer applied in production systems that include fertilizer trees (Schoeneberger 2009; Sileshi et al. 2014). Fertilizer trees are nitrogen-fixing leguminous trees commonly used in cereal reduction systems and pastures to improve the availability of N to crops or grass (Sileshi et al. 2014). Fertilizer trees widely raised under FMNR include species of *Faidherbia*, *Parkia*, *Tamarind*, *Vachellia*, *Senegalia* and *Acacia*. Fertilizer trees add more than 60 kg N ha^{-1} per year through biological nitrogen fixation (Akinnifesi et al. 2010). This contribution can reduce the need for N application by about 75% (Akinnifesi et al. 2010). For example, farmers who apply 5 Mg ha^{-1} of tree prunings can maintain maize yield of up to 5 Mg ha^{-1} without adding inorganic fertilizer (Sileshi et al. 2014). Significant yield increases have been found from fertilizer trees even when the recommended fertilizer amount was reduced by between 25 and 50% (Sileshi et al. 2014). Farms with fertilizer trees tend to receive less N fertilizer and therefore may have fewer N_2O emissions.

Regenerating trees can reduce N_2O by creating safety nets for nutrients (Nair et al. 2021). Trees reduce emissions associated with fertilizer application by taking up excess nutrients during the crop growing season or off-season nutrients when crops are not in the field. Trees can also take up nitrogen that leaches from the topsoil during intense rainfall. These nutrients are then recycled to the topsoil via decomposition of litterfall. The functions of trees as safety nets have been observed in agroforestry systems without specific reference to FMNR. It is important to note that the effect of trees on N_2O emissions is variable, with emerging evidence showing higher N_2O emission in soils under N-fixing tree species than soils N-fixing crop species.

Trees in pasture can reduce CH_4 emissions by improving emissions intensity, for example by providing more digestible feed or allowing a grazing strategy of moving cattle in a rotational stocking system (Schoeneberger 2009). By improving emission intensity, trees provide greater overall gain from feed efficiency due to shade-induced microclimate changes (Schoeneberger 2009). The role of parkland trees in improving livestock production in the Sahel has been documented in the literature (Bayala et al. 2014a, b). Parkland trees provide green fodder that complements crop residues for livestock feeds. Trees such as Faidherbia provide high-quality fodder that can reduce CH_4 emissions.

FMNR can conserve biomass and soil carbon in existing forests by providing items that would otherwise be obtained from forests, thereby reducing pressure on forests that causes deforestation and forest degradation. The collection of wood and fodder from forests is one of the leading causes of forest degradation (Darkoh 1998; Dimobe et al. 2015). Estimates of fuelwood production from parklands (1.6 t ha^{-1}

year^{-1}), windbreaks (2.0 t ha^{-1} year^{-1}) or trees scattered in farms (6.3 t ha^{-1} year^{-1}) are sufficient for meeting the current fuelwood need of 486–500 kg person^{-1} year^{-1} for up to 10 households of 3–7 people (Kuyah et al. 2020). FMNR can also mitigate climate change through carbon substitution. Trees provide woodfuel that substitute fossil fuel, and wood that substitutes materials (e.g. steel, concrete, bricks) that require high energy input during production. Regeneration of trees can also reduce equipment run in areas with trees, thereby reducing fossil fuel consumption.

3.6 Case Studies

Two case studies are chosen to highlight evidence of FMNR for mitigation and adaptation in drylands. The studies document legume woody species in agroforestry systems and their role in climate change adaptation and mitigation in the communes of Aguié and Mayahi in Maradi, Niger. The communes of Aguié (13°51′21″ N, 08°18′12″ E) and Mayahi (13°57′48.2″ N, 07°40′19″ E) are located in the northeast of the region of Maradi with an average elevation of 434 m (Aguié) and 385 m (Mayahi). The two communes receive between 150 and 350 mm of rain annually. A systematic random sampling method was used to collect data from 80 plots measuring 2500 m^2 (33 plots in Aguié and 47 in Mayahi). In each plot, the name of the species, total tree height and diameter at breast height (DBH = 1.3 m) was recorded for trees with DBH >5 cm. Purposive sampling was used to identify presence of legume species on farmers croplands. An open-ended questionnaire was used to collect socio-economic and ecological information about the importance of legumes trees found on croplands. A total of 24 (19 in Aguié and 15 in Mayahi) woody legume species were documented in the two communes. Above and belowground biomass was estimated using a generalized biomass estimation equation by Chave et al. (2014); wood density was obtained from the global wood density database. The IPCC default value (0.47) was used to convert dry matter to biomass carbon. The results highlight the role of legume woody species in climate change adaptation and mitigation.

3.6.1 Livelihood Benefits From Legume Woody Species

Woody vegetation provides a range of ecosystem services that are critical to the resilience of dryland species and people. Field inventories and interview with farmers in Aguié and Mayahi communes in Niger identified 24 legume tree species regenerated and protected by farmers (Table 3.1). The study found that farmers maintain legume trees for soil fertility improvement, food and nutritional benefits (fruits, leaves), timber, fodder, firewood, income and climate services. Legumes improve soil fertility through biological nitrogen fixation; their leaves are also used as green manure. Tree species such as *Senegalia*, *Faidherbia*, *Parkia*, *Tamarindus*

Table 3.1 Adaptation services and socio-economic and ecological implications of legume woody species documented in the communes of Aguié and Mayahi, Maradi, Niger

Species	Adaptation services	Socio-economic and ecological benefits
Faidherbia albida	Land restoration, soil fertility improvement, soil protection, livestock feed, climate information, medicine, wood	Food and nutritional security, income, climate readiness, improved coping strategy
Parkia biglobosa	Food (fruits, seeds, leaves), soil fertility improvement, wood, forage production, medicine	Food and nutritional security, income
Parkinsonia aculeata	Fodder (pods and leaves), soil fertility, medicine, fruits	Income
Senegalia ataxacantha	Soil fertility improvement, land restoration, forage production, medicine	Income
Vachellia nilotica	Land restoration, wood, forage production, tannin, medicine	Income, health
Senegalia senegal	Gum production, forage production, soil fertility improvement, medicine, wood	Income
Vachellia seyal	Fuelwood, gum production, soil fertility, fodder, medicine	Income, food and nutritional security, health
Vachellia sieberiana	Timber, firewood, medicine, soil fertility, forage	Income
Vachellia tortilis	Forage production, green manure, medicine, timber and firewood, soil fertility improvement	Cultural, income, health
Cassia sieberiana	Soil fertility improvement, wood, medicine, ornamental tree	Health, income, cultural
Senna singueana	Soil fertility improvement, wood, medicine	Resilient ecosystem, food and nutritional security, health
Delonix regia	Soil fertility improvement, food (fruit), wood, firewood (dry fruits), medicine, cultural—land ownership	Food and nutritional security, health; land tenure and ownership
Dichrostachys cinerea	Soil fertility improvement, timber and firewood, medicine, fodder	Income
Piliostigma reticulatum	Soil fertility improvement, timber and firewood, medicine, fodder	Income, food and nutritional security
Detarium microcarpum	Food (fruits), soil protection (against wind and water erosion), microclimate, medicine, wood	Income, food and nutritional security
Pterocarpus erinaceus	Soil fertility improvement, fodder, wood, medicine	Income
Prosopis africana	Soil fertility improvement, medicine, forage production	Income
Prosopis juliflora	Firewood, medicine	Income
Senegalia polyacantha	Soil fertility improvement, firewood, fodder, medicine	Income
Albizia chevalieri	Soil restoration, timber, fodder, firewood, medicine	Income

(continued)

Table 3.1 (continued)

Species	Adaptation services	Socio-economic and ecological benefits
Bauhinia rufescens	Soil fertility improvement, fodder, fire-wood, medicine	Income
Entada africana	Soil fertility improvement, timber and firewood, fodder, medicine	Income
Tamarindus indica	Food (fruits and vegetables), fertiliser tree, fodder, medicine	Nutritional diversity, income
Dalbergia sissoo	Timber, green manure, forage production, medicine	Income

and *Vachellia* are important fertilizer trees in drylands (Akinnifesi et al. 2010; Sileshi et al. 2014). The soil of a farm with six to nine woody species, of which two to three fix nitrogen, will be healthier than a farm with only *G. senegalensis* and *Piliostigma reticulatum*, which do not fix nitrogen. Farmers were aware of and mentioned the role of leaves of deciduous species as a source of soil organic matter. For example, fallen leaves of *Senna singueana* were mentioned as important for improving soil fertility. *Acacia* trees are common in cropland, pasture fields and windbreaks where they regulate microclimate, improve water infiltration and improve overall soil fertility. *Faidherbia* is used as a biological indicator of start of rainy or dry season, depending on the phenology. Besides fixing nitrogen, *Faidherbia* sheds its leaves during the cropping season thus reducing competition with annual crops. *Faidherbia* has leaves during the dry season, providing protein-rich forage to livestock during this critical period of quality feed shortage.

Legume woody species constitute a great source of income for the two communes. For instance, the pods from *Faidherbia*, *V. tortilis*, *Parkia* and *Detarium microcarpum*, are collected by women and young people for sell in urban areas where they are used as animal feed. The leaves and other parts of the trees are sold in the market for income. Gum production is a major livelihood activity for farmers in the two communes. Famers use income from sell of gum to buy crop seeds and food items for family consumption during the lean season. Leaves and other parts of *Cassia sieberiana* are traded among the two communities. By increasing and diversifying income, legumes trees provide a coping mechanism for farmers when faced with adverse effects of climate change, for example crop failure following drought.

Trees also contribute to health and nutrition of the two communes. The majority of the trees are medically important to the local populations (Table 3.1). For example, farmers mentioned the use of roots of baobab, leaves of *S. singueana*, and the stem, leaves and fruits of *Parkia* and *Vitellaria* to treat malaria. They consider every part of *C. sieberiana* to be medically important. Some of the trees also provide fruits and leaves that are used as food by the people. Locals use seeds of *Parkia* to make the traditional condiment known as *sumbala* or *soumbala* or *dawadawa*. Fruits, leaves and seeds of *Tamarind*, *Parkia* and Baobab as well as gum arabic and leaves from other legume tree species are important sources of nutrients to the people of Aguié and Mayahi.

The majority of the legume woody plant recorded in the agroforestry systems of the communes of Aguié and Mayahi provide fodder (Table 3.1). Farmers also maintain trees (e.g. *Faidherbia*) in their pasture. Forage is collected by pruning some branches of legume woody species such as *Faidherbia*, *B. rufescens*, *P. erinaceus* and *Acacia* spp., trees on the field or transported to the village for animal feedings. The rest of branches are used for fuelwood and the animal drops are taken back to agroforestry systems for soil improvement. Field discussion revealed that farmers maintain fodder trees and shrubs for their animals or for sale. Livestock keeping is a common cause of conflict between the herdsmen and farmers during the rainy and dry season in the two communes. To mitigate the conflict, some herdsmen sign contracts with farmers on the use of their trees as fodder in exchange of animal drops as manure for the farms.

Table 3.2 Mean carbon stock (Mg ha^{-1}) of legume woody species (with more than 2 individuals; diameter at breast height >5 cm) found in the communes of Aguié and Mayahi, Maradi, Niger

	No of trees		Diameter at breast height		Biomass carbon (Mg ha^{-1})	
Species	Aguié	Mayahi	Aguié	Mayahi	Aguié	Mayahi
Faidherbia albida	36	115	35.70 ± 17.30	24.36 ± 17.10	2.11 ± 2.06	1.23 ± 2.4
Piliostigma reticulatum	29	58	21.23 ± 10.35	17.26 ± 10.00	0.61 ± 0.67	0.45 ± 0.66
Senegalia senegal	20	7	13.84 ± 6.98	14.33 ± 7.95		0.092 ± 0.14
Vachellia tortilis	17	48	16.28 ± 5.86	19.11 ± 9.23	0.24 ± 0.18	0.50 ± 0.55
Vachellia nilotica	13	7	22.76 ± 17.06	25.16 ± 11.08	1.27 ± 2.61	1.17 ± 1.22
Senna singueana	12	5	9.08 ± 2.94	8.41 ± 3.65	0.048 ± 0.031	0.034 ± 0.026
Prosopis africana	8	2	54.86 ± 28.01	46.97 ± 32.65	8.12 ± 8.45	6.76 ± 8.23
Bauhinia rufescens	4	4	11.54 ± 4.76	12.02 ± 2.02	0.085 ± 0.07	0.10 ± 0.05
Cassia sieberiana	4	2	19.98 ± 13.53	9.08 ± 2.93	0.90 ± 1.17	0.053 ± 0.05
Tamarindus indica	3	4	40.87 ± 6.44	44.98 ± 9.59	4.28 ± 2.66	5.76 ± 3.22
Vachellia seyal	2		20.22 ± 5.18		0.55 ± 0.44	
Dichrostachys cinerea		2		7.80 ± 0.23		0.0024 ± 00.00

3.6.2 Carbon Sequestration in Legume Woody Species

Legume woody species play a major role in climate mitigation through carbon sequestration. Table 3.2 shows the average carbon stocks in selected woody legumes inventoried in the communes of Aguié and Mayahi, Maradi, Niger. Carbon stocks were highest under *P. africana* (3.08 Mg ha^{-1}) in Aguié and *V. tortilis* (3.11 Mg ha^{-1}) in Mayahi. Exotic legume tree species such as *Parkinsonia aculeata*, *Delonix regia* and *Prosopis juliflora* are used in the reforestation program in the agroforestry systems in the two communes, a key strategy in carbon enhancement. Farmers use harvested wood products to build houses, make artefacts, and other wood-based equipment, providing an option of long-term carbon storage. Farmers protect their trees through community tree protection in croplands and through tree protection law and environmental patrols within the area. The environmental protection officers of the two communes sensitize the farmers to protect trees and fight desertification. The legume woody species recorded in Aguié and Mayahi are protected trees species in Niger. These measures could lead to increased carbon sequestration.

3.7 Conclusions

This chapter presented evidence regarding the dual role of FMNR in reducing emission of GHG and carbon sequestration (mitigation) as well as reducing the vulnerability and increasing the resilience of societies and ecosystems in drylands (adaptation). FMNR contributes to climate change mitigation while benefiting land managers in different ways. It creates multifunctional landscapes in drylands which restores lost ecosystem services. At adaptation level, FMNR combines provisioning (food and nutritional security and income diversification) with creation of resilient production systems. Tree foods, fodder, firewood, fibre and biochemicals provide a safety net and diversify income for communities facing climate threats. FMNR supports crop and livestock production by moderating microclimate, improving soil fertility and providing inputs into different farm enterprises. Species promoted under FMNR need to have the potential to meet the most important farmers' needs thus reduction in vulnerability among the affected communities.

FMNR approach has proved successful in regard to restoring landscapes and improving livelihoods of rural communities in Niger and neighbouring countries. Similar approaches have already started in other parts of Africa. Some are spontaneous, based on traditional knowledge, while others employ the same model found in West Africa to FMNR in their regions. It takes longer for farmers to realize income from the sale of trees, tree products or carbon credits. This reduces the attractiveness of tree-based systems in drylands, where the focus is meeting immediate household needs. In some cases, finding markets for commodities such as fodder or firewood may be problematic in the rural areas, or when everyone has trees. Integrating tree growing with activities that generate income in the short term can buffer farmers. Tree-based systems can be designed to provide short-term benefits in terms of income or materials such as firewood and tree foods or fodder, as farmers wait for future anticipated benefits. Integration of FMNR into other systems will lead to greater adoption and benefits to more people in drylands.

References

Akinnifesi FK, Ajayi OC, Sileshi G, Chirwa PW, Chianu J (2010) Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron Sustain Dev 30:615–629

Allen M, Diakite M, Gana I (2009) Regreening the Sahel: a case study of farmer managed natural regeneration in Mali. Sahel Eco, Bamako

Bastin JF, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner CM, Crowther TW (2019) The global tree restoration potential. Science 365:76–79

Bayala J, Ky-Dembele C, Kalinganire A, Olivier A, Nantoumé H (2014a) A review of pasture and fodder production and productivity for small ruminants in the Sahel. World Agroforestry Centre (ICRAF), Nairobi

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014b) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Bayala J, Sanou J, Bazié HR, Coe R, Kalinganire A, Sinclair FL (2020) Regenerated trees in farmers' fields increase soil carbon across the Sahel. Agrofor Syst 94:401–415

Binam JN, Place F, Kalinganire A, Hamade S, Boureima M, Tougiani A, Dakouo J, Mounkoro B, Diaminatou S, Badji M, Diop M (2015) Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa. Environ Econ Policy Stud 17:543–575

Brenner AJ, Jarvis PG, Van Den Beldt RJ (1995) Windbreak-crop interactions in the Sahel. 2. Growth response of millet in shelter. Agric For Meteorol 75:235–262

Brown DR, Dettmann P, Rinaudo T, Tefera H, Tofu A (2011) Poverty alleviation and environmental restoration using the clean development mechanism: a case study from Humbo, Ethiopia. Environ Manag 48:322–333

Cervigni R, Morris M (2016) Confronting drought in Africa's drylands: opportunities for enhancing resilience. World Bank, Washington

Charney J, Stone PH, Quirk WJ (1975) Drought in the Sahara: a biogeophysical feedback mechanism. Science 187:434–435

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol 20:3177–3190

Crawford A, Shteir S, Chaves D (2016) Farmer managed natural regeneration; evidence gap analysis. World Vision Australia, Melbourne

Darkoh MBK (1998) The nature, causes and consequences of desertification in the drylands of Africa. Land Degrad Dev 9:1–20

Davies J, Barchiesi S, Ogali CJ, Welling R, Dalton J, Laban P (2016) Water in drylands: adapting to scarcity through integrated management, Gland, Switzerland

Davis B, Di Giuseppe S, Zezza A (2017) Are African households (not) leaving agriculture? Patterns of households' income sources in rural Sub-Saharan Africa. Food Policy 67:153–174

Dimobe K, Ouédraogo A, Soma S, Goetze D, Porembski S, Thiombiano A (2015) Identification of driving factors of land degradation and deforestation in the Wildlife Reserve of Bontioli (Burkina Faso, West Africa). Glob Ecol Conserv 4:559–571

Dimobe K, Mensah S, Goetze D, Ouédraogo A, Kuyah S, Porembski S, Thiombiano A (2018) Aboveground biomass partitioning and additive models for *Combretum glutinosum* and *Terminalia laxiflora* in West Africa. Biomass Bioenergy 115:151–159

Dimobe K, Kuyah S, Dabré Z, Ouédraogo A, Thiombiano A (2019) Diversity-carbon stock relationship across vegetation types in W National park in Burkina Faso. For Ecol Manag 438:243–254

Dossa EL, Fernandes ECM, Reid WS, Ezui K (2008) Above-and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agrofor Syst 72: 103–115

Duguma B, Gockowski J, Bakala J (2001) Smallholder cacao (Theobroma cacao Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. Agrofor Syst 51:177–188

Duguma LA, Nzyoka J, Minang PA, Bernard F (2017) How agroforestry propels achievement of nationally determined contributions. Policy brief. World Agroforestry (ICRAF), Nairobi

ELD Initiative and UNEP (2015) The economics of land degradation in Africa: benefits of action outweigh the costs. ELD Initiative, Bonn

Faye MD, Weber JC, Mounkoro B, Dakouo J-M (2010) Contribution of parkland trees to farmers' livelihoods: a case study from Mali. Dev Pract 20:428–434

Francis R, Weston P, Birch J (2015) The social, environmental and economic benefits of farmer managed natural regeneration. World Vision, Melbourne, pp 6–23

Garrity DP, Bayala J (2019) Zinder: farmer-managed natural regeneration of Sahelian parklands in Niger. In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry Centre, Nairobi, pp 151–172

Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A, Larwanou M, Bayala J (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Secur 2:197–214

Griscom Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, Schlesinger WH, Shoch D, Siikamäki JV, Smith P, Woodbury P (2017) Natural climate solutions. Proc Natl Acad Sci 114:11645–11650

Haglund E, Ndjeunga J, Snook L, Pasternak D (2011) Dry land tree management for improved household livelihoods: farmer managed natural regeneration in Niger. J Environ Manag 92: 1696–1705

Iiyama M, Derero A, Kelemu K, Muthuri C, Kinuthia R, Ayenkulu E, Kiptot E, Hadgu K, Mowo J, Sinclair FL (2017) Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. Agrofor Syst 91:271–293

IPBES (2018) The IPBES assessment report on land degradation and restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn

IPCC (2018) Summary for policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

IPCC (2021) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jamnadass R, Place F, Torquebiau E, Malézieux E, Liyama M, Sileshi G, Kehlenbeck K, Masters E, McMullin S, Dawson I (2013) Agroforestry, food and nutritional security. World Agroforestry Centre (ICRAF), Nairobi

Jindal R, Swallow B, Kerr J (2008) Forestry-based carbon sequestration projects in Africa: potential benefits and challenges. Nat Res Forum 32:116–130

Jonsson K, Ong CK, Odongo JCW (1999) Influence of scattered nere and karite trees on microclimate, soil fertility and millet yield in Burkina Faso. Exp Agric 35:39–53

Kamara CS, Haque I (1992) *Faidherbia albida* and its effects on Ethiopian highland Vertisols. Agrofor Syst 18:17–29

Kibru T, Husseini R, Birhane E, Haggar J, Solomon N (2021) Farmers' perception and reasons for practicing farmer managed natural regeneration in Tigray, Ethiopia. Agrofor Syst 95:1327–1342

Kim D-G, Kirschbaum MU, Beedy TL (2016) Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: synthesizing available data and suggestions for future studies. Agric Ecosyst Environ 226:65–78

Kindt R, Kalinganire A, Larwanou M, Belem M, Dakouo JM, Bayala J, Kairé M (2008) Species accumulation within land use and tree diameter categories in Burkina Faso, Mali, Niger and Senegal. Biodivers Conserv 17:1883–1905

Kizito F, Dragila M, Sene M, Lufafa A, Diedhiou I, Dick RP, Selker JS, Dossa E, Khouma M, Badiane A, Ndiaye S (2006) Seasonal soil water variation and root patterns between two semi-arid shrubs co-existing with Pearl millet in Senegal, West Africa. J Arid Environ 67:436–455

Kizito F, Sene M, Dragila MI, Lufafa A, Diedhiou I, Dossa E, Cuenca R, Selker J, Dick RP (2007) Soil water balance of annual crop–native shrub systems in Senegal's peanut basin: the missing link. Agric Water Manag 90:137–148

Kuyah S, Sileshi GW, Njoloma J, Mng'omba S, Neufeldt H (2014) Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. Biomass Bioenergy 66:214–222

Kuyah S, Öborn I, Jonsson M, Dahlin AS, Barrios E, Muthuri C, Malmer A, Nyaga J, Magaju C, Namirembe S, Nyberg Y (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. Int J Biodivers Sci Ecosyst Serv Manage 12:255–273

Kuyah S, Öborn I, Jonsson M (2017) Regulating ecosystem services delivered in agroforestry systems. In: Dagar J, Tewari V (eds) Agroforestry. Springer, Singapore, pp 797–815

Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron Sustain Dev 39:47. https://doi.org/10.1007/s13593-019-0589-8

Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Kuntashula E, Dimobe K, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes, vol 1. Springer, Singapore, pp 135–167

Kuyah S, Sileshi GW, Nkurunziza L, Chirinda N, Ndayisaba PC, Dimobe K, Öborn I (2021) Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agron Sustain Dev 41:1–21

Laestadius L, Maginnis S, Minnemeyer S, Potapov S, Saint-Laurent C, Sizer N (2011) Mapping opportunities for forest landscape restoration. Unasylva 62:47–48

Larwanou M, Reij C (2011) Farmer managed natural regeneration in Niger: a key to environmental stability, agricultural intensification, and diversification. In: Innovations as key to the green revolution in Africa. Springer, Cham, pp 1311–1319

Larwanou M, Saadou M (2011) The role of human interventions in tree dynamics and environmental rehabilitation in the Sahel zone of Niger. J Arid Environ 75:194–200

Larwanou M, Abdoulaye M, Reij C (2006) Etude de la régénération naturelle assistée dans la Région de Zinder (Niger): une première exploration d'un phénomène spectaculaire

McMullin S, Njogu K, Wekesa B, Gachuiri A, Ngethe E, Stadlmayr B, Jamnadass R, Kehlenbeck K (2019) Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. Food Secur 11:1355–1372

MEA (2005) Ecosystems and human well-being: desertification synthesis. World Resources Institute (WRI), Washington

Michels K, Lamers JPA, Buerkert A (1998) Effects of windbreak species and mulching on wind erosion and millet yield in the Sahel. Exp Agric 34:449–464

Miller DC, Muñoz-Mora JC, Christiaensen L (2017) Prevalence, economic contribution, and determinants of trees on farms across Sub-Saharan Africa. Forest Policy Econ 84:47–61

Minnemeyer S, Laestadius L, Sizer N, Saint-Laurent C, Potapov P (2011) A world of opportunity. The global partnership on forest landscape restoration. World Resources Institute, South Dakota State University and IUCN

Mirzabaev Mirzabaev A, Wu J, Evans J, García-Oliva F, Hussein IA, Iqbal MH, Kimutai J, Knowles T, Meza F, Nedjroaoui D, Tena F (2019) Desertification. In: Shukla PR, Skeg J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva

Moore E, van Dijk T, Asenga A, Bongers F, Sambalino F, Veenendaal E, Lohbeck M (2020) Species selection and management under farmer managed natural regeneration in Dodoma, Tanzania. Front Forests Global Change 3:123

Nair PR, Kumar BM, Nair VD (2021) An introduction to agroforestry-four decades of scientific developments. Springer, Cham

Ndegwa G, Iiyama M, Anhuf D, Nehren U, Schlüter S (2017) Tree establishment and management on farms in the drylands: evaluation of different systems adopted by small-scale farmers in Mutomo District, Kenya. Agrofor Syst 91:1043–1055

Nkonya E, Mirzabaev A, von Braun J (2016) Economics of land degradation and improvement – a global assessment for sustainable development. Springer, Cham

Öborn I, Bargués Tobella A, Bostedt G, Hörnell A, Knutsson P, Lindvall K, Mpairwe D, Mureithi S, Nyberg G, Nyberg Y, Schumann B, Turinawe A, Vågen T, Wakjira D, Winowiecki L, Wredle E (2022) Restoring rangelands for nutrition and health for humans and livestock. Proceeding International Grassland Conference, Kenya Agricultural and Livestock Research Organization. https://uknowledge.uky.edu/igc/24/1-2/28

Olinto P, Beegle K, Sobrado C, Uematsu H (2013) The state of the poor: Where are the poor, where is extreme poverty harder to end, and what is the current profile of the world's poor. Econ Premise 125:1–8

Place F, Garrity D, Mohan S, Agostini P (2016) Tree-based production Systems for Africa's drylands. World Bank, Washington

Pramova E, Locatelli B, Djoudi H, Somorin OA (2012) Forests and trees for social adaptation to climate variability and change. Wiley Interdiscip Rev 3:581–596

Pricope NG, Husak G, Lopez-Carr D, Funk C, Michaelsen J (2013) The climate-population nexus in the East African Horn: emerging degradation trends in rangeland and pastoral livelihood zones. Glob Environ Chang 23:1525–1541

Reij C, Tappan G, Smale M (2009) Re-greening the Sahel: farmer-led innovation in Burkina Faso and Niger. International Food Policy Research Institute (IPFRI), Washington

Rhoades C (1995) Seasonal pattern of nitrogen mineralization and soil moisture beneath Faidherbia albida (syn Acacia albida) in central malawi. Agrofor Syst 29:133–145

Rinaudo T (2012) Farmer managed natural regeneration: exceptional impact of a novel approach to reforestation in Sub-Saharan Africa. In: Agricultural options for the poor-a handbook for those who serve them. Educational Concerns for Hunger Organisation (Echo Inc), North Fort Myers

Rinaudo T, Muller A, Morris M (2019) Farmer managed natural regeneration (FMNR) manual. World Vision Australia, Melbourne

Rosenstock TS, Wilkes A, Jallo C, Namoi N, Bulusu M, Suber M, Mboi D, Mulia R, Simelton E, Richards M, Gurwick N (2019) Making trees count: measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. Agric Ecosyst Environ 284: 106569

Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, Dreyer E (1999) Reverse phenology and dry-season water uptake by Faidherbia albida (Del.) A. Chev. in an agroforestry parkland of Sudanese west Africa. Funct Ecol 13:460–472

Safriel U, Adeel Z, Niemeijer D, Puigdefabregas J, White R, Lal R, Winslow M, Ziedler J, Prince S, Archer E, King C (2005) Dryland systems. In: Ecosystems and human well-being: current state

and trends. Findings of the condition and trends working group. Island Press, Washington, pp 623–662
Samba SAN, Camiré C, Margolis HA (2001) Allometry and rainfall interception of Cordyla pinnata in a semi-arid agroforestry parkland, Senegal. For Ecol Manag 154:277–288
Sanou J, Zougmoré R, Bayala J, Teklehaimanot Z (2010) Soil infiltrability and water content as affected by Baobab *(Adansonia digitata* L.) and Néré (*Parkia biglobosa* (Jacq.) Benth.) trees in farmed parklands of West Africa. Soil Use Manag 26:75–81
Sanou J, Bayala J, Teklehaimanot Z, Bazié P (2012) Effect of shading by baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) on yields of millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) in parkland systems in Burkina Faso, West Africa. Agrofor Syst 85: 431–441
Sawadogo H (2011) Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. Int J Agric Sustain 9:120–128
Schoeneberger MM (2009) Agroforestry: working trees for sequestering carbon on agricultural lands. Agrofor Syst 75:27–37
Sileshi GW, Mafongoya PL, Akinnifesi FK, Phiri E, Chirwa P, Beedy T, Makumba W, Nyamadzawo G, Njoloma J, Wuta M, Nyamugafata P (2014) Agroforestry: fertilizer trees. Encycl Agric Food Syst 1:222–234
Sinare H, Gordon LJ (2015) Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa. Agric Ecosyst Environ 200:186–199
Svendsen M, Ewing M, Msangi S (2009) Measuring irrigation performance in Africa. International Food Policy Research Institute (IFPRI), Washington
Takimoto A, Nair PR, Nair VD (2008) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166
Takimoto A, Nair VD, Nair PR (2009) Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. Agrofor Syst 76:11–25
Tougiani A, Guero C, Rinaudo T (2009) Community mobilisation for improved livelihoods through tree crop management in Niger. GeoJournal 74:377–389
UNEP (1997) World atlas of desertification, 2nd edn. United Nations Environment Programme (UNEP), London
United Nations (2017) World population prospects. Department of Economics Social affairs. United Nations, New York, p 24
Westerberg V, Doku A, Damnyag L (2019) Reversing land degradation in drylands: the case for farmer managed natural regeneration (FMNR) in the Upper West Region of Ghana. Report for the economics of land degradation initiative in the framework of the "Reversing Land Degradation in Africa by Scaling-up Evergreen Agriculture" project. The Economics of Land Degradation
Weston P, Hong R, Kaboré C, Kull CA (2015) Farmer-managed natural regeneration enhances rural livelihoods in dryland West Africa. Environ Manag 55:1402–1417
WMO (2019) State of the climate in Africa, 2019. WMO, Geneva
Yirdaw E, Tigabu M, Monge Monge AA (2017) Rehabilitation of degraded dryland ecosystems–review. Silva Fennica 51(1):1673
Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. World Agroforestry Center, Nairobi
Zougmoré R, Jalloh A, Tioro A (2014) Climate-smart soil water and nutrient management options in semiarid West Africa: a review of evidence and analysis of stone bunds and zaï techniques. Agric Food Secur 3:16

Chapter 4
Urban and Peri-Urban Agroforestry to Sustain Livelihood and Food Security in the Face of Global Environmental Change and Epidemic Threats

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Abstract Many cities in tropical regions of Sub-Saharan Africa and Asia are at the forefront of global environmental change, and are now faced with the increasing risk of floods, droughts, coastal erosion, sea level rise, storm surges and saline water intrusion. The increasing human population, rapid urbanization, on-going climate change, biodiversity loss, natural resource depletion, reliance on fossil fuels and pesticides, migration flows and growing wealth inequity contribute to food crisis, poverty, malnutrition and threats due to epidemics like COVID-19 in urban areas. During the last 2 years, the world faced not only the health-related crisis leading to huge causalities from the COVID-19 epidemic but also food crisis mainly in urban areas due to scarcity of vegetables, fruits and dairy products. Therefore, suitable management strategies need to be identified to minimize the impact of growing urban lands on food security, environmental services and climate change mitigation. In this context, increased attention is being focused on the role of forestry/agroforestry, vertical agriculture and horticulture in urban and peri-urban environments. Therefore, this review explores the opportunity associated with urban agroforestry systems and greening the landscapes to ensure the utilization of urban soils for food production, improving livelihoods, food and nutritional security, adaptation to climate vulnerability, climate change mitigation and biodiversity conservation.

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4.1 Introduction

The increase in urban population is now a global phenomenon. The global urban population of 54% in 2020 is expected to be 60% by 2030 (Knorr et al. 2018) and the rate of urbanization is remarkably high in the developing world. Urban population as percentage of the total world population in developed and developing regions, respectively, was 23.6 and 76.4 in 2018, and is projected to be 16.8 and 83.2% in 2050 (UN 2018). By 2030, two-thirds of the world population will be urbanized of which 80% will be in low- to middle-income countries (Lal 2020) and the future growth of population will almost entirely occur in urban areas of developing countries. The majority of the most populous cities are in Asia, especially in China and India. The ever-increasing demand for water, food and other essential commodities in urban areas is a challenge and the problem is going to increase further as more and more people migrate to urban centres for better opportunities. Even though cities cover less than 3% of world's surface, yet they consume 75% of the natural resources (Borelli et al. 2017). The rapid urbanization will further accelerate the demand for increased quantity of high-value foods such as fruits, vegetables, milk, meat and eggs, from the shrinking land, water and biodiversity resources. Asia and Africa are two continents which have the most people prone to both under-nourishment and malnourishment. The wide spread occurrence of COVID-19 has aggravated the already serious problems of hunger and the hidden-hunger. There is always scarcity of good-quality water and per capita availability has been reducing since 1951 when it was 5177 m^3 and reduced to 1588 m^3 in 2010 and expected to be 1341 m^3 in 2025 and 1140 m^3 in 2050 (CWC 2010).

The UN Intergovernmental Panel on Climate Change (IPCC), in its various reports (IPCC 2007, 2014, 2021), has provided strong scientific evidence of global warming. It is now clear that climate change is being caused by people that threaten the livelihoods and well-being of all people and societies. The extreme climate events such as storms, heat waves, droughts and devastating floods are intensifying. The extreme climate events cause direct destruction and have pervasive impacts on food security, infectious disease transmission and economic stability that continue to occur for many years more so in urban areas. The rapid urbanization and on-going global changes related to environment and climate change, migration flows in search of livelihood, natural resource depletion, fluctuating global economies, natural disasters such as frequent cyclones and spread of Corona, and malnutrition-related diseases will contribute towards food crisis and poverty in urban areas.

Globally, urban and peri-urban agriculture (UPA) including agroforestry is gaining attention from governments, and many international organizations like the United Nations Conference on Environment and Development (UNCED), United Nations Centre for Human Settlements (UNCHS), the Food and Agriculture

Organisation of United Nations (FAO) and the Consultative Group on International Agricultural Research (CGIAR)—Urban Harvest have been supporting the cause. Since 1999, FAO has been implementing a global project entitled 'Growing Greener Cities', with main objectives of (1) ensuring political and institutional commitment, securing land and water for UPA, (2) ensuring product quality while protecting the environment, (3) ensuring participation of all stakeholders and (4) securing market for the produce (FAO 2009).

Salbitano et al. (2015) emphasized that urban and peri-urban forestry and trees, together with agroforestry systems, urban horticulture, green spaces, tree lines and hedges, parks, green roofs and walls, and riparian corridors form the physical and functional urban green infrastructure of the city region and constitute the critical dynamic elements of urban and peri-urban landscapes. The different urban agroforestry systems have provisioning and cultural functions, besides their regulatory services such as infiltration of storm water, mitigate urban heat island effects, carbon sequestration and recycling of urban wastes (Lin et al. 2015; Lovell 2010; Wortman and Lovell 2013). There is growing evidence that urban and peri-urban agriculture, forestry and agroforestry can play a role in reducing vulnerability to climate change (Lee-Smith 2010; Prain et al. 2010; Lwasa et al. 2015).

Considering the potential benefits of urban agroforestry for improved ecosystem functioning, we discuss the role of agroforestry systems in urban and peri-urban areas in food and nutritional security, biodiversity conservation, carbon sequestration and climate change mitigation under global environmental change.

4.2 Environmental Concerns for Urban Agroforestry

4.2.1 Growing Urban Population

During the past century, the high urban population growth has taken place on $<3\%$ of the global terrestrial surface, yet having global impacts in terms of 78% of carbon emissions, 60% of residential water use and 76% of wood used for industrial purposes (Brown 2001). The increasing unsustainable consumption patterns have caused problems of air pollution, water scarcity and waste generation, and human health in Southeast Asia (UNEP 2016). Cities are hotspots of production, consumption and waste generation, including greenhouse gas emissions (Grimm et al. 2008a, b). Estimates suggest that cities are responsible for 75% of global CO_2 emissions, with transport and buildings being among the largest contributors (UNEP 2021). Air quality is one of the leading environmental threats to public health. Air pollution issues are especially acute in rapidly urbanizing and industrializing nations such as India and China. About 90% of people in Sub-Saharan Africa are exposed to indoor air pollution, impacting both economies and livelihoods while contributing to increased emissions of greenhouse gases. Human population growth is a major contributor to global warming as humans use fossil fuels for their economic growth and to support improved lifestyles; therefore, increasing urbanization will further deteriorate the environment. When fossil fuels are burned, these emit carbon dioxide into the atmosphere which traps warm air inside like a greenhouse.

The most disturbing phenomenon of increased urbanization in developing economies is because the rural people are mostly depending upon agriculture for their sustenance which has met setbacks because of shrinking land holdings and vulnerable cropping systems to climate change. The urbanization is a key driver of global environmental change (Brown 2001; Grimmond 2007; Grimm et al. 2008a; Wu 2014; UNEP 2021). For example, cities are main contributors to air, water and noise pollution leading to climate change, as urban activities are major sources of greenhouse gas emissions. At the same time, urban areas are now the centres of economic growth, innovations, arts and policy development. The supply of basic services and standards of living are frequently, albeit not always, higher among urban populations than their rural counterparts.

4.2.2 Nutritional Insecurity

The malnutrition problem among poor population in urban slum areas is a matter of concern and the nutritional requirement has to be met. With growing affluence and increasing nutritional awareness among the city dwellers about nutrition, there will be increased demand for vegetables, fruits, eggs, meat, dairy products and even flowers. It has been pointed out in the 'Report on the state of food security in urban India' by the M. S. Swaminathan Research Foundation; the situation in urban areas is often overlooked during discussions on food and nutrition security (MSSRF 2010). There is considerable food and nutritional insecurity in the urban areas, the situation being worse in smaller towns. Especially vulnerable are women and children; about 50% of the women are anaemic, and undernourishment resulting in severe energy deficiency is rampant among women (MSSRF 2010).

People living in urban areas have much less control over the supply and quality of the food they consume as compared to the rural population. The food prices, especially those of vegetables, fruits and pulses, which heavily influence the quantum of their intake, are often subject to huge fluctuations due to many factors ranging from the vagaries of the monsoon to spread of diseases to the changes in price of crude oil in the international market and to the changes in policies governing import and export of agricultural commodities. The situation was grave during recent COVID-19 spread when many lessons were learnt. People in urban areas do not have any control over the use of pesticides and other chemicals used in producing the food, which has serious implications for nutritional value and safety of the food consumed. Instances where farmers grow organic food for their own consumption and insecticide laden produce for sale have been reported.

4.2.3 Increasing Use of Natural Resources and Loss of Biodiversity

It is clear that human population is using more natural resources and services through overfishing, deforestation and emission of more carbon dioxide into the atmosphere than forests can sequester. According to Global Footprint Network (2014), humanity currently uses 74% more than what the planet's ecosystems can regenerate or 1.7 Earths. At current population levels, our planet has only 1.7 global hectares (gha) of biologically productive surface area per person. The world-average ecological footprint was 2.75 global hectares per person, and the average biocapacity was 1.63 global hectares. This means there is a global deficit of 1.1 global hectares per person.

The populations of agricultural and domestic animal species have increased alongside humans, whereas biodiversity has declined globally (Crist et al. 2017). Land conversion for crop and animal agriculture is one of the main drivers of habitat loss and according to latest report of RED List of endangered species of the IUCN released in December 2020, thousands of animal species are at critical risk of becoming extinct due to unsustainable farming and fishing methods and climate change (IUCN 2020). Recently, Simkin et al. (2022) projected the growing impact of urban expansion on 30,000 species of mammals, birds, reptiles and amphibians from 2015 to 2050. This study revealed that urbanization is a serious driver of biodiversity loss comparable to that of agriculture and forestry ((Laurance and Engert 2022). In rapidly urbanizing regions of Sub-Sahara Africa, South America and Meso-America, and Southeast Asia, expansion of urbanization will be greatest threat in the foreseeable future (Simkin et al. 2022). Studies have shown that these tropical regions are home to much of the earth's biodiversity, as sufficiently large intact habitats are required for disturbance sensitive species (Sloan et al. 2014). The urban land-use intensity, increasing number of invasive species and rapidly co-evolving changes contribute to decline of biodiversity in urban areas (Shochat et al. 2006; Aronson et al. 2014).

Over 70 wild relatives of some of the world's most important crops are threatened with extinction, mostly these plants, native to Mexico, Guatemala, El Salvador and Honduras, provide genetic resources that are necessary to breed crops worldwide with greater resilience to climate change, pests and diseases, as well as to improve yields (Goettsch et al. 2021). Rapid urbanization in tropical regions may be a threat to wild genetic resources of crops, horticulture plants and domesticated animals.

4.2.4 Waste Disposal and Use of Wastewater

The waste disposal is already a problem in almost every city especially in developing countries impacting the general health problems. With high costs of water for agriculture, farmers tend to utilize wastewater from sewer lines, thus exposing the production to chemical and biological contamination. We are facing the scarcity of water on one hand and generating about 356 km^3 per year of wastewater across the globe. Only 50% water is treated to primary level and 6.7% is used in agriculture in 123 countries (Sato et al. 2013). However, the disparity in water treatment among different countries is alarming; only 8–32% of total wastewater generated is treated in developing Middle East and North Africa (MENA) countries, Latin America and Asia in comparison to 67–73% in Europe and America (Sato et al. 2013). Because investments in treatment facilities have not kept pace with persistent increases in urban population and the wastewater volumes generated, on an average, wastewater treatment is limited to <27% in most of developing countries of Latin America, MENA and Asia (Sato et al. 2013).

The use of poor-quality water in various activities including urban agro(forestry) is inevitable, more so in future, which will further deteriorate the urban environment. Therefore, we need to develop the better technical methods and policy guidelines for handling untreated wastewater on farms and recommendations for its use in plantation-based agroforestry for protecting farm workers and consumers from the potentially harmful pathogens and chemicals.

4.2.5 Impacts of the COVID-19 Pandemic

The COVID-19 pandemic has disrupted human lives and livelihoods and proved to be a stress test for the social–ecological systems at the forest–agriculture interface mainly in developing countries, as part of rural–urban systems and the global economy as such (Duguma et al. 2021). There was food crisis even in urban areas of the developed countries. On the basis of synthesis of studies by Dessler and Parson (2019), there are many similarities between public issue cycles in natural resources management and those in the current COVID-19 pandemic. Several workers have stressed the need for a more resilient, diversity-based form of land use in which human vulnerability is buffered (Karesh et al. 2012; Valenzuela 2016; Duguma et al. 2021). Though some workers reported positive impacts of the lockdown ‘anthropause’ on environmental conditions (emission of GHGs, etc.) were likely only for short term, while progress towards sustainable development goals has suffered a setback especially for social aspects such as livelihood, employment and income. Under these stress conditions, development of fruit and vegetable parks in urban areas and dairy-based agroforests in peri-urban areas could be handy to meet the essential requirements of urban population. A major challenge created by the COVID-19 pandemic is disrupting access to fresh and nutritious food at affordable prices to large and growing urban population (Lal 2020). The problem is worsened by the lack of or weak infrastructure and poor institutional support. Thus, there is a need to adopt more resilient food systems, reduce food waste along the supply chain and strengthen the growth of local agricultural capabilities through homegardening and urban agriculture.

4.3 Historical Background of Urban and Peri-Urban Agroforestry

Though the urban and peri-urban agroforestry as a science is a new concept, the cultivation of trees (both fruit and avenue) and ornamental plants is as old as the urban settlements. Trees have probably been a part of towns and cities since their first development (Miller 2004). Since agriculture led to the first permanent settlements after hunting and gathering of food from wild, it stands to reason that domestication of plants and animals (present day agroforestry) were part of the community. Food, wood and water supply relatively close to the urban settlements were vital in ancient cities due to reasons of transport, safety and need (at present designated as urban agroforestry). Archaeological excavations corroborate early tree domestication around the settlements in South Asia. The evidence of this dates back to the Mesolithic period (10,000–4000 BC) when fruits of 63 plants including Indian Jujube (*Ziziphus* spp.), *bael* (*Aegle marmelos*), goose berry (*Emblica officinalis*), figs (*Ficus* spp.), *mahua* (*Madhuca indica*), mango (*Mangifera indica*), banana (*Musa* spp.), etc. were reported, consumed and domesticated near the habitats (Randhawa 1980) showing the ancient roots of urban agro(forestry) as most of these are also found now cultivated in urban areas. Incidentally, some scattered references occur in different texts of the *Vedic* literature in India and elsewhere which prove that the cultivation of many fruit trees and requirement of livestock in agriculture and mixed economy based on trees was in existence long back and may also be traced in protohistory chalcolithic periods (2000–700 BC) of civilization (Raychaudhuri and Roy 1993).

The role of many common tree species such as *khejri* (*Prosopis cineraria*), *aswattha* (*Ficus religiosa*), *palasa* (*Butea monosperma*), *aamram* (*Mangifera indica*), *narikelah* (*Cocos nucifera*) and *varana* (*Crataeva nurvala*) as sacred trees in Indian folk-life has been mentioned in ancient literature of Rig Veda, Atharva Veda and other Indian scriptures (Mann and Saxena 1980; Rao 1996; Malhotra 1998), which are also considered sacred in present times. Emperor Ashoka, a great Indian ruler (273–232 BC), encouraged a system of arbore-horticulture based on banana, mango, jack fruit and grapes. Besides trees (mostly bearing fruits) along road sides and open places the cultivation of medicinal herbs and trees was the accepted norm in ancient times as shown on 14 Rock Edicts of Ashoka (257 BC). Thus, the concept of social forestry and homegarden was prevalent in earlier times.

Dagar and Tewari (2017) and Borelli et al. (2017) highlighted several historic depictions of ancient agroforests and are mentioned here in brief. It is reported that about 4000 years ago, the Egyptians used to transplant trees with the balls of soil and trees were valued for fruits, shade and aesthetics and planted in gardens and around places of worship and in palaces (Chadwick 1971) showing their intention of developing tree-planting techniques. The hanging Gardens of Babylon built by King Nebuchadnezzar II, more than 2500 years ago, are described in a number of texts and it is assumed that the gardens included several agroforestry systems/ practices (Miller 2004) involving various tree-based agricultural and horticultural components (agroforestry of present times). Roman cities developed a wide typology of city gardens with prominent components of agroforestry in urban and peri-urban areas. The gardens in every home of ancient Pompeii, especially around the Amphitheatre, are tangible examples of the organization of green spaces in cities. The archaeo-botanical remains of grapes (*Vitis vinifera*) associated with tree species such as elm (*Ulmus* spp.), field maple (*Acer campestre*) and hornbeam (*Carpinus* spp.); and of *Juglans* and *Castanea* remains in association with pollens of edible vegetables near Neapolis suggest the use of space for multiple resource-production and multipurpose agroforests in and near the cities. Similarly, the walled medieval cities in Europe were surprising laboratories of tree-based agricultural practices (agroforestry) in urban areas. In scarcity of energy and food supply from surrounding territories (peri-urban areas), urban communities felt the need to find alternative solutions in terms of producing food, energy and medicines within the city walls by planting fruit and medicine yielding trees and herbs as is evident even today in the European medieval cities, gardens of most fragile trees and shrubs do exist (Borelli et al. 2017). The civilizations of Maya, Inca and Aztecs built large cities with monumental architecture of agroforests and agriculture as is evident from drawings and descriptions of pre-Columbian America (Lentz et al. 2014). The decision of a permanent settlement in ancient times was linked to the presence of tree species with multiple uses and could be combined with multiple land uses. For example, the use of acorn meals (based on *Quercus* and relative genera) is well noted in the diet of native Americans (Merriam 1918, cited by Borelli et al. 2017), and the presence of oaks was a crucial aspect in deciding the wintering cities for native Americans (McCarthy 1993).

Food and Agriculture Organization published an account on 'Perception of Forests' in which many authors have expressed interesting citations from different regions showing that trees have been in the centre of human civilization from ancient times (fao.org/3/y9882e/y9882e1-19htm). It is mentioned that trees are prominent in both the Bible and the Koran. Arboreal references in these holy books reflect the place of trees in cultures of millennia ago—their uses, the local species of importance and moreover their inspirational and symbolic significance, based on the perception of the tree as symbol of the life given by the Creator. These references are found from the first book of the Bible, which contains a reference to the 'tree of life' in the Garden of Eden to the last book of the New Testament, which refers to the tree of life as a major feature in Paradise. Tree species such as apple (*Malus domestica*), almond (*Prunus dulcis*), cypress (*Cupressus sempervirens*), date palm (*Phoenix dactylifera*), fig (*Ficus cari*ca), pine (*Pinus halepensis*, *P. pinea*), pistachio (*Pistacea vera*), walnut (*Juglans regia*) and willow (*Salix* spp.) and many others have been mentioned in the religious books in one or the other relevance. With the continuous influence of these books over thousands of years, particular species (e.g. the cedar of Lebanon, *Cedrus libani*; sycamore fig, *Ficus sycamorus* in Egyptian mythology; *Ficus religiosa* in Hindu mythology) and certain forests and groves have acquired great—even sacred—importance, which still holds today and may contribute to their protection and conservation. Many of these trees are found grown around the places of worship in urban and peri-urban areas showing their importance since ancient periods. Modern concerns with conserving the forests and biodiversity are perhaps a natural extension of the logic of ancient tree rites. Evidently, the sacred grove is today a biosphere reserve, a natural heritage site or protected area (biodiversity park).

In West Africa, the role of trees in this connection is more often linked to historical reminiscences and veneration: a holy person stopped under a particular tree to rest and pray, and thus the tree has become a site for pilgrimage and meditation. They also rely on the appearance or shape of particular part of a tree. For example, the long pendulous fruits of *Kigelia africana* have caused the tree to be associated with fertility in human beings. The tamarind tree (*Tamarindus indica*) frequently found growing next to termite mounds is always green and considered to be auspicious. The Mbuti people of the Ituri forest in the Democratic Republic of the Congo decorate bark-cloths with abstract imagery that expresses the life, motion, sound and shape of their forest world; where men prepare the bark-cloths from the inner bark of about six different species of trees and women prepare the dyes and paints from a variety of roots, fruits and leaves which they collect from the forest for decoration (Moraga 1996).

Historical records, legends and folk songs all throw light on the sacred groves of Tamil Nadu in India. The first authentic report of the sacred groves is found in the memoirs of Ward and Conner written in 1827, cited in the 1891 census of Travancore state (Census Commissioner's Office, India 1894). Brandis (1897), the first Inspector General of Forests in India, reported on the sacred groves in the hill ranges of the Salem district in the Madras Presidency. These groves were peri-urban multifunctional stands. Several inscriptions on stone slabs and copper plates record that ruler of that time granted land to maintain temple gardens and a great variety of flowering plants were cultivated in these gardens for aesthetic look and offering to the deity to perform pujas (Hindu prayers). Even after the introduction and proliferation of Christianity and Islam, the sacred groves remained as cradles of ancient rural civilization not only in Tamil Nadu, but also in many other states of India. It is evident that the traditions are continued and many sacred groves occur in almost every part of Tamil Nadu and their area ranges from a few trees to hundreds of hectares. Most of the sacred groves represent the natural climax vegetation of their geographical location. The exact extent is not known but according to an assessment documented in 1995, a total of 13,270 sacred groves were present in India, out of which 448 were in Tamil Nadu (Rao 1996). Of these, 79 ranged in size from 0.01 to 900 ha and together embraced 10,511 ha of vegetation cover-138 ha comprised totally undisturbed vegetation, and 3188 ha with open canopy. However, in another estimate, the number of groves in the country may be as high as 100,000 to 150,000 (Vajpeyi 2000). Natural history studies during the two previous centuries (Mateer 1883; Logan 1906) also signify that the people in southern parts of peninsular India traditionally used their homesteads for a variety of needs such as food, energy, shelter, medicines and other purposes showing that urban and peri-urban agroforestry (as defined now) was at central stage in meeting the livelihood and aesthetic requirements since ancient times.

From the beginning of the twenty-first century, the rapid evolution of agricultural technologies has brought new forms of plant cultivation, allowing for multiple productions and circularity (e.g. in aquaponics systems), but also through the creation of common metabolisms in urban buildings, as for the growing examples of vertical farming and rooftop agriculture projects (La Rosa et al. 2014; Orsini et al. 2020). The role and functions of urban agriculture in developing countries have been addressed in several review papers (Bryld 2003; de Bon et al. 2010; de Zeeuw et al. 2011; Gallaher et al. 2013; Orsini et al. 2013; Hamilton et al. 2014; Poulsen et al. 2015; Lin and Egerer 2018) but very few articles have been brought out on urban and peri-urban agroforestry (Borelli et al. 2017).

4.4 Typology of Urban and Peri-Urban Agroforestry

Most of the early literature is on urban agriculture, as there was no specific discipline of agroforestry. To describe the typology of urban and surrounding areas, Wu (2008) used and described term 'Urban Ecology' in socio-ecological perspective in which cities were regarded as socio-economic systems and humans the primary components. There was no integration with natural sciences but ecological theories such as competition, niche partitioning and succession were used as metaphors to explain spatial differentiation of land uses and people in cities (Wu 2008; Cadenasso and Pickett 2013). Further, in Europe after World War II, the urban ecology was considered a component of 'ecological science' through in-depth studies on the distribution and richness of plants and animals in and around cities (Wu 2014) and the approach used in those studies was bio-ecological. Despite these earlier studies, since last two decades, urban ecology has been regarded as part of mainstream ecology and the aspects such as increasing urbanization and its effect on the environment, as well as a paradigm shift in ecology focusing on non-equilibrium and patch dynamics and an increasing focus on sustainable cities are some of the reasons for the increasing research interest in cities (Wu 2014; Pickett et al. 2016; Shackleton et al. 2021). Therefore, Wu (2014) proposed a broad definition of urban ecology 'the study of spatiotemporal patterns, environmental impacts, and sustainability of urbanisation with emphasis on biodiversity, ecosystem processes, and ecosystem services'. Other disciplines such as urban geography, urban sociology and anthropology, urban planning and ecological engineering are related to urban ecology, but our focus here remains only on urban landscape ecology, urban forestry/agroforestry and urban agriculture.

The relationship to landscape ecology, the science of studying the relation between spatial patterns (spatial heterogeneity) and processes (ecological and socio-economic) at various scales, is quite clear that urban ecology has developed into an urban landscape ecology. Lin and Egerer (2018) described *urban agriculture* as the production of different types of food (e.g. vegetables, fruit, mushrooms, spices, eggs, milk, meat) in a variety of urban green spaces (e.g. community or allotment gardens, private gardens, rooftop gardens, orchards, peri-urban areas).

Urban and peri-urban agriculture (UPA) can be defined as the growing of plants and the raising of animals for food and other uses within and around cities and towns, and related activities such as the production and delivery of inputs, processing and marketing of products (FAO 2007) and often includes horticulture, livestock production, milk and egg production, fish farming and other enterprises. Although homegardens constitute a well-established agroforestry practice, they were also treated part of UPA. Many urban gardens consist of an intimate mixture of crops and trees. When the agricultural commodities are produced through interaction of different components on a same unit of landscape, then these may be interpreted as urban and peri-urban agroforestry (UPAF) practices. However, urban and peri-urban forestry (UPF) is a sub-discipline of forestry and refers to the research and management of tree-dominated urban green areas focusing on their 'physiological, sociological, economic and aesthetic benefits' for society (Koninjnendijk and Gauthier 2006) and also its ecological importance. In close urban systems, UPF and UPAF are complementary to each other and cannot and must not be separated as the basic purpose is the same to meet the basic requirements of the people mainly for food, fuelwood, aesthetics and environmental services. However, in present context, only UPAF will be dealt. The deliberate combination of trees crops and/or livestock (agroforestry) can result in more sustainable and resilient systems offering a wide range of ecosystem services, both in the global North and South (Nair 2007).

Peri-urban can be described as the landscape interface between town and countryside and is the rural–urban transition zone. Despite of urban land uses, the fringes remain largely open with the majority of the land with agricultural, woodland or other rural uses. Peri-urban agriculture, in turn, is the cultivation undertaken in places on the fringes of urban areas. FAO (2001) defines urban and peri-urban agriculture as 'an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows and raises, processes and distributes a diversity of agricultural products, using largely human, land and water resources, products and services found in and around that urban area, and helps in closing energy loops and transforming waste into biodiversity'. Thus, urban and peri-urban agroforestry (UPAF) can broadly be defined as integration of woody perennials (trees, shrubs, palms, bamboos, etc.), crops, non-conventional herbaceous plants and/or livestock (including aquaculture) on the same management unit while optimizing the biological, physical and ecological interventions and achieving environmental, social and economic advantages for land users and other population in and around urban ecologies. Though the cultivation of avenue trees, plantations and ornamental plants is as old as urban settlements. UPAF practices within and around cities compete for resources (land, water, energy, labour) that could also serve other purposes to satisfy the requirements of the urban population. First and the foremost role of UPAF is production and distribution of food, firewood and other agricultural commodities in and around cities. It integrates into the urban economic and ecological systems.

In the past, urban and peri-urban agroforestry (UPAF) was mostly described as part of 'urban and peri-urban agriculture' or 'urban forestry'. Many of the articles published in specialized journals such as *Arboriculture and Urban Forestry*, *Arboricultural Journal*, *Landscape and Urban Planning*, *Urban Forestry* and *Urban Greening* also frame issues related to agroforestry as urban forestry issues. There is also a recent tendency in bulking many of the urban agriculture, forestry and agroforestry practices under 'urban green infrastructure'. As a result, much of the literature is not clear on the role of agroforestry in its own right. There is also a great deal of confusion in terminology in the literature. Salbitano et al. (2015) provide a very clear representation of the Urban Green Infrastructure (UGI) framework and its components. Accordingly, the components of the urban green infrastructure are: (1) horticulture, (2) urban agriculture, (3) urban and peri-urban agroforestry, (4) urban and peri-urban forestry, (5) urban arboriculture and (6) urban green space. Following this classification, in the rest of this chapter, we will discuss UPAF as a distinct component of green infrastructure so that attributions can be made to the role of agroforestry in future work.

Urban and peri-urban agroforestry is an integrated, interdisciplinary, participatory and strategic approach to planning and managing tree resources in and around cities. 'Urban forests' can be defined as networks or systems comprising all woodlands, groups of trees and individual trees located in urban and peri-urban areas; they include, therefore, forests, street trees, trees in parks and gardens, and trees in derelict corners (http://www.fao.org/sustainable-forestmanagement/toolbox/modules/urban-and-peri-urban-forestry). In agroforestry mode, more precaution is to be taken in selection of associate crop. It involves the assessment, planning, planting, maintenance, preservation and monitoring of urban and peri-urban tree resources as well as suitability of the crop. Sustainable urban development is crucial for ensuring the quality of life of the world's people. Agroforests and trees in urban and peri-urban environments, if properly managed, can make important contributions to the planning, design and management of sustainable, resilient landscapes. Urban and peri-urban agroforestry contributes to sustainable development goals.

Globally, urban and peri-urban agriculture including agroforestry is gaining attention from governments, and many international organizations like the United Nations Conference on Environment and Development (UNCED), United Nations Centre for Human Settlements (UNCHS), the Food and Agriculture Organisation of United Nations (FAO) and the Consultative Group on International Agricultural Research (CGIAR)—Urban Harvest have been supporting the cause. Since 1999, FAO has been implementing a global project entitled 'Growing Greener Cities', with main objectives (1) ensuring political and institutional commitment, (2) securing land and water for UPA, (3) ensuring product quality while protecting the environment, (4) ensuring participation of all stakeholders and (5) securing market for the produce (FAO 2009). Recently, urban and peri-urban agroforestry has attracted the global scientific community and quite impressive work has been conducted in this field. For example, Amsterdam has devoted over 350 ha of land to urban gardens for the production of fresh food and other goods for the urban population (Van Leeuwen 2010), while in Dar es Salaam, Tanzania, 90% of the leafy vegetables and 60% of the milk consumed in the city are produced within or around the urban area (Lee-Smith and Prain 2006). A study by Odurukwe (2004) demonstrated the relevant role of agroforestry practices in peri-urban cities of Abia State, Nigeria, namely Uzakoli, Obehie and Isuikwuato, where the inhabitants practise multi-storey homegardens to improve their livelihoods through income generation by selling goods such as fruits, food crops, vegetables, leaves, seeds, bark, fuelwood, etc. In this context, 17% of the respondents reported to earn additional (after sustaining their family) annual income of between US$180 and 270, 52% earn between 90 and US$180 and 31% of households earn around US$90. In order to address the negative impact of climate change and urbanization, the Bobo-Dioulasso (second largest city of Burkina Faso in Sub-Saharan Africa) municipality has promoted multifunctional urban and peri-urban agroforestry playing a key role in the national economy (Di Leo et al. 2016; Borelli et al. 2017).

The Government of India has also launched the *Smart Cities Mission* (SCM) with the objective to promote sustainable and inclusive cities that provide core infrastructure and give a decent quality of life to its citizens, a clean and sustainable environment and application of 'Smart' solutions. The top five development categories—transportation, energy and ecology, water and sanitation, housing and economy—constitute almost 80% of the SCM budget. This will help in developing smart agroforestry systems in urban and peri-urban areas and emphasis may also be given on judicious use of wastewater. This will help in developing smart agroforestry systems in urban and peri-urban areas, some success stories are available in India to develop urban agroforests (Box 4.1; NAAS 2022).

Box 4.1 Some Successful Models of Urban Green Infrastructure in India (NAAS 2022)

- Maharashtra, the first ever urban forestry project developed on a 16-ha barren strip of land by TERRE under a public-private partnership model as a corporate social responsibility initiative. It is rich in biodiversity of flora and fauna.
- Another good example is of Aravalli Biodiversity Park of Gurugram (Haryana), created on 153.7 ha degraded mined landscape by a unique partnership between the municipal corporation and residents. It has now hundreds of species of flowering trees, shrubs and medicinal herbs and attracting more than 200 bird species.
- On the occasion of World Environmental Day under the Nagar Van Scheme it has been decided that 200 Urban (Agro)forests will be developed across the country in the next five years with a renewed focus on people's participation and collaboration between the Forest Department, Municipal bodies, NGOs, corporates and local citizens. This is a good way to involve and educate people, especially youth about importance of UPAF and mitigating climate change.

(continued)

Box 4.1 (continued)

4.4.1 Main Urban and Peri-Urban Agroforestry Practices

In present scenario, urban agriculture is generally practised on small-to-medium size holdings within cities for growing annual and tree crops, raising small livestock, poultry and fish for home consumption or sale. The peri-urban agriculture is aimed to meet part of food demand of urban population by efficient utilization of land in the periphery of the cities and towns. The integration of agroforests in urban contexts consists in a variety of systems such as riparian and forest buffers, windbreaks, greenways, vertical gardens, roof gardens, homegardens, parks and landscapes, roadside and street plantations, development of lakes and aquacultures. In peri-urban areas, cultivation of vegetables, fruits, mushroom, ornamental plants, and fodder and development of dairy, poultry and aquaculture if properly planned and managed can play very important and relevant role in food and nutrition security and environment improvement. Ecosystem services provided by urban and peri-urban agroforestry may include provisioning services such as food, freshwater, raw materials and medicinal resources; cultural services such as recreation, mental and physical health, tourism, aesthetic values and spiritual enrichment; regulating services in terms of improved local environment, carbon sequestration, pollution control, wastewater management, pollination and biodiversity enrichment; and supporting services to provide habitat for migratory and local species and maintaining genetic diversity.

4.4.1.1 Homegardens for Food Security and Livelihood Enhancement

The homegarden is a farming system multi-storey combination of various trees, palms and crops (sometimes in association with domestic animals), which combines different physical, social and economic functions on land around the family home to supplement supply of fresh food and other commodities at the household level. These provide easy day-to-day access to fresh vegetables and fruits, leading to enriched and balanced diets by supplementing nutrients like proteins, vitamins and minerals (Galhena et al. 2013). Homegardens play a key role in enhancing food security of urban and peri-urban dwellers. These practices can contribute to local food security in several ways, by fostering direct access to quality and healthy food; enhancing family income, thanks to savings on food bills and on generation of additional income from sale of garden production; and providing food products year-round, especially during periods of food scarcity (Montagnini 2006; Dagar et al. 2020).

In Africa, people often grow different kind of fruit trees in their homegardens. The common tree species in homegardens are avocados (*Persea americana)*, banana (*Musa sapientum*), guava (*Psidium guajava*), mango (*Mangifera indica*), papaya (*Carica papaya*), pineapple (*Ananas comosus*) and citrus fruits. In islands of South-east Asia and Pacific and Caribbean, people meet their food and nutrition security through homegardens which provide the provision of local and traditional fruits (mango, avocado, oranges, lemon, papaya, banana, jackfruit, etc.), coconut, vegetables (tomatoes, eggplant, okra, beans, amaranthus, cucurbits, etc.) and also some herbs (oregano, coriander, rosemary basil and mint). In addition, multi-storey homegardens can provide medicinal plants to the families and communities that maintain them, both for subsistence and marketing purposes. The relevance of traditional herbal medicines is witnessed by their widespread use in developing countries, especially in Africa where up to 80% of population is still dependent on them (WHO 2002). Furthermore, if not directly consumed, medicinal resources can be sold for generating additional income. Thus, homegardens can improve food security, diversity, nutritious value and the microenvironment around the family home (Kumar and Nair 2004; Dagar and Minhas 2016: Dagar et al. 2020).

Some Examples/Success Stories

- Keeping in view of *vertical farming* (multi-storey homegardens) in urban areas, Despommier and Carter (2011) developed the idea of a multi-storey green building in which layers of crops and shrubs could be grown on each floor vertically to feed the population of urban areas. Mbow et al. (2014) recognized the importance of implementing urban and peri-urban agroforestry practices as effective contribution towards the achievement of a relevant part of Sustainable Development Goals (SDGs), particularly to the Goal 11*: Making cities and communities more sustainable*, *resilient*, *and healthy.* There lie several examples and success stories in different parts of the world under each category. In many developing countries such as Pacific and Caribbean islands, sizeable urban population is dependent on products (fruits, vegetables, eggs, meat, medicinal herbs, etc.) of peri-urban homegardens. One interesting example is of peri-urban multi-storey homegardens in cities of Abia State in Nigeria which improved the economic status of local population. Bobo-Dioulasso, second largest city of Burkina Faso in Sub-Saharan Africa, represents a unique model of sustainable development of urban homegardens tackling climate change through multifunctional agro-systems in and around the city. The development of the city is one of the outcomes of the UN-Habitat Cities and Climate Change Initiatives (UN-Habitat 2014).

- Recently, urban and peri-urban agroforestry has attracted the global scientific community and quite impressive work has been conducted in this field. For example, Amsterdam has devoted over 350 ha of land to urban gardens for the production of fresh food and other goods for the urban population (Van Leeuwen 2010), while in Dar es Salaam, Tanzania, 90% of the leafy vegetables and 60% of the milk consumed in the city are produced in UPAF within or around the urban area (Lee-Smith and Prain 2006).
- A study by Odurukwe (2004) demonstrated the relevant role of agroforestry practices in peri-urban cities of Abia State, Nigeria, namely Uzakoli, Obehie and Isuikwuato, where the inhabitants practise multi-storey homegardens to improve their livelihoods through income generation by selling goods such as fruits, food crops, vegetables, leaves, seeds, bark, fuelwood, etc. In this context, 17% of the respondents reported to earn additional (after sustaining their family) annual income of between US$180 and 270, 52% earn between 90 and US$180 and 31% of households earn around US$90. In order to address the negative impact of climate change and urbanization, the Bobo-Dioulasso (second largest city of Burkina Faso in Sub-Saharan Africa) municipality has promoted multifunctional urban and peri-urban agroforestry playing a key role in the national economy (Di Leo et al. 2016; Borelli et al. 2017).
- In India, the homegardens of peri-urban areas of Port Blair in Andaman Islands, are most popular because of the equatorial climate, which is optimal for growing most of the crops including plantations. These homesteads are unique being more or less coconut-based with an array of intercrops or mixed crops resulting in multi-storey cropping system, thereby efficiently harnessing solar radiation and using soil moisture and nutrients. Spice trees like nutmeg (*Myristica fragrans*) and cinnamon (*Cinnamomum zeylanicum*) and fruit trees like papaya and lemon occupy the second storey. They are grown mostly under the coconut and occasionally under the areca nut. Clove is found in both the first and the second storey as well. Cinnamon is grown commonly in interspaces of coconut and under the areca nut. Banana is grown always relatively in open where water from the house drains. Coconut, areca nut, coffee, rubber and cashew are main plantation crops;

and banana, papaya, mango, guava, pineapple, sapota, lemon, lime, mandarin, jackfruit and custard apple are main fruits grown but not on a large scale. Among spices, black pepper, cardamom and clove are major crops. Tapioca, ginger and turmeric are also cultivated frequently. Vegetables and fodder grasses form the ground cover.

4.4.1.2 Fodder Banks

Throughout history, there are numerous examples of diachronic and synchronic agroforestry and agrisilvopastoral systems, long before these terms were coined and the modern sense of the practices codified (Borelli et al. 2017). Fodder banks represent a stand of multipurpose forage legumes and other non-conventional protein sources established on farmland or in urban and peri-urban settings (Chakeredza et al. 2007). Fodder banks are widely used by smallholder dairy farmers particularly in East and Southern Africa. Fodder harvested from such stands can be used in the formulation of diets balanced for the key nutrients in cost-efficient way. The establishment of fodder banks has gathered prominence under cut-and-carry systems for peri-urban dairy in Kenya and Malawi (Chakeredza et al. 2007). Fodder banks provide opportunities for market-oriented peri-urban dairy production and livestock fattening. Homegardens may play important role in meeting the fodder and feed requirement in management of urban animal stock.

In Indian sub-continent, the urban and peri-urban farming not only includes growing of food crops but also animal husbandry, agroforestry and horticulture. Fodder production and livestock farming are major farming activities in peri-urban areas (NAAS 2022). In a base-line survey conducted in peri-urban areas of city Faisalabad in Pakistan, it was found that Egyptian clover (*Trifolium alexandrium*), maize (*Zea mays*) and sorghum (*Sorghum bicolor*) were the major commercial fodder crops of the area grown by around 90% of the farmers while pearl millet (*Pennisetum glaucum*) and oat (*Avena sativum*) also cultivated at small scale. Most of the farmers are small and marginal and livestock-based farming is the major source of income for their livelihood (Ul-Allah et al. 2014) so is true in India. Most of the family sale milk and also spare fodder to the needy. They also cultivate vegetables. Most of the farming units are in agroforestry mode either in silvopastoral or agrisilvicultural mode. Lal et al. (2020) also reported that Egyptian clover and sorghum could be cultivated successfully with *Eucalyptus camaldulensis* and *Populus deltoides* in peri-urban areas using sewage water without having toxic elements. Fodder trees such as species of *Acacia*, *Cassia*, *Dalbergia*, *Pongamia*, *Prosopis*, *Azadirachta*, *Melia*, *Morus*, *Terminalia*, *Moringa*, *Tamarindus*, *Ficus*, *Leucaena*, etc. planted as boundary trees in teaching institutes, factories, streets and road-sides and on open gardens may contribute partially to the fodder requirement of small ruminants and mopping of grasses from lawns and grounds also may be used as fodder.

4.4.1.3 Horticulture-Based UPAF

The Government of India has paid greater attention to UPA and among many other steps, towards the end of the 11th Five-Year Plan, a peri-urban vegetable production scheme was launched which has made a good progress (DAC 2011). The Working Groups on Horticulture constituted by the Planning Commission for XII Five-Year Plan (2012–2017), under UPA initiatives had advocated attention not only for growing fruits and vegetables but also for environmental services and health care. A National Dialogue organized jointly by the National Horticulture Board and the Indian Institute of Horticultural Research (IIHR) also discussed urban and peri-urban horticulture and advocated for full land utilization, interior and exterior landscaping, vertical gardens and terrace cultivation of fruits and vegetables and mushroom culture (Singh and Malhotra 2013). Most of the horticultural schemes blended with fruit trees and multi-purpose trees such as *Moringa oleifera* may be adapted as UPAF.

4.5 Potential of Urban and Peri-Urban Agroforestry

4.5.1 Biodiversity Conservation and Ecosystem Services

Urban homegardens (Nair 1993), forest gardens (Hart 1996) and food forests (Bukowski and Munsell 2018) fall on a spectrum of urban agroforestry. A mature urban forest garden may include trees and shrubs, vines, herbaceous plants and tubers, fungi, as well as domesticated animals (Hart 1996; Nair 1993). Species diversity, composition, and use of traditional homegardens is a function of place and culture, and site suitability where plants could be selected for cultivation based on food, fodder, fuel, medicine, religion, or aesthetic needs and preferences (Kumar and Nair 2004). Smaller-scale urban homegardens have been shown to have the greatest species richness with predominance of ornamental and aesthetic species (Drescher et al. 2006; Kumar et al. 1994).

Studies on homegardens in African and Asian regions indicates that medicinal plants constitute at least 25% of the total homegarden species and serve biocultural repositories (Kumar et al. 1994). Many urban homegardens in Africa are biodiversity-rich (Akinnifesi et al. 2010). Because of their multi-commodity structure, urban homegardens offer food and nutritional security to the urban and peri-urban population, besides acting as a source of consistent cash income. These also help in getting a buffer to food insecurity during the lean season, providing habitat protection, soil and water conservation, environmental services and a high rate of carbon sequestration (Dagar 2014; Dagar et al. 2014). The multiple-strata systems as exemplified by parks, forests, and home or community gardens, provide connectivity to support plant, insect and vertebrate biodiversity (Hemmelgarn and Munsell 2021).

Studies have shown that urban agriculture with high vegetation diversity can have positive effects on invertebrate biodiversity in urban systems, whereas garden structures or management practices providing food and nesting resources can play an important role for maintaining vertebrate diversity in urban areas (see Lin et al. 2015). The allotment gardens can support urban pollinators for long periods of time.

The urban agroforestry systems are generally multifunctional systems providing sociocultural, economic, and ecological benefits (Lovell 2010; Nair 1993). The ecosystem services from multiple-strata urban agroforestry systems include pollution mitigation (Escobedo et al. 2011), carbon sequestration (Kumar 2011), biodiversity for wildlife habitat, microclimate control, and runoff reduction (Lovell and Taylor 2013; Sperling and Lortie 2010), which are dependent on the diversity and vegetative structure of the system (Drescher et al. 2006).

4.5.2 Utilization of Urban Soils for Food Production

Urban soils are called Anthropic soils, Anthrosols or Technosols (FAO/UNESCO 1990) because anthropogenic control of pedogenic processes leads to drastic alterations in soil properties. In general, these are comprised of highly disturbed and manipulated materials altered through mixing, filling, transportation, and other perturbations caused by construction-related activities. The major constraints of developing these soils for agroforestry or growing vegetables include high heterogeneity, large temporal and special variability, presence of artefacts and contamination by inorganic and organic pollutants (Lal 2020). In general, these soils are characterized by poor physical properties (e.g. high bulk density, low water infiltration rate, low plant available water capacity and susceptibility to drought), unfavourable chemical properties (e.g. low soil fertility, nutrient imbalance and low soil organic carbon concentration and stock) and low activity and species diversity of soil biota (Lal 2020).

Soil contamination by heavy metals [i.e. lead (Pb), arsenic (As), and cadmium (Cd)] and organic pollutants [i.e. polycyclic aromatic hydrocarbons (PAHs), antibiotics and petroleum products] are among the major constraints limiting the use of urban soils for food production (Menefee and Hettiarachichi 2018). These problems must be addressed to produce healthy and safe food. Indeed, with adequate management and bioremediation, the pathway from contaminated soil to humans via food can be minimized, and high yield obtained with judicious management of inputs (McDougall et al. 2019). Bioavailability of heavy metals and organic pollutants can be reduced by input of soil amendments including compost, mulch, recycling of the biomass and use of engineered media, which enhance soil health and promote activity and species diversity of soil biota. Therefore, restoration and sustainable management of these soils for agronomic productivity and nutritional quality of vegetables and fruits grown on these soils requires judicious use of technologies and skill. The liquid and solid organic household waste generated along with other biomass (i.e. lawn clippings, leaf litter, treated wastewater and harvested rainwater, etc.) may be judiciously used to improving soil quality and functionality and alleviating soil-related constraints for developing UPAF. Many local organic pesticides (e.g. from neem *Azadirechta indica* tree) and fertilizers (e.g. peels of banana, orange, onion, kitchen wastes, etc.) are commonly used these days.

For moderate levels of metals and metalloids in wastewater, there is no particular management needed if the soils are calcareous; however, there can be problem in acidic soils, which require lime treatment and when irrigating with wastewater containing elevated levels of sodium, soil structure deterioration may occur and we require application of calcium source such as gypsum. Care has also to be taken regarding detrimental effects of salts, nitrates, metals and pathogens reaching groundwater; shallower is watertable more is the danger.

Vertical farming, based on a cyclic economy involving aquaponics and hydroponics, is an innovative option in urban agriculture (Despomier 2018). Just as in agricultural lands, indiscriminate use of chemicals, water, and other inputs must be avoided. Similarly, judicious use of inputs is critical to obtaining high yields and safe produce in homegardening (McDougall et al. 2019). Because of heavy human traffic, the risks of soil compaction (particularly in peri-urban areas) must be minimized by improving and sustaining soil structure of the surface layer by mulching and use of compost to enhance the activity of earthworms and other biota. Scarcity of good quality topsoil can be addressed by using imported soils, mainly from municipal waste collected at a secluded place. Rather than sprinklers, drip irrigation may be essential to improving water use efficiency.

Experiments conducted in Minicoy (Lakshadweep) where most of the homegardens are with coconut-based have revealed that 98% of nitrogen and 28% of each of potassium and phosphorus could be substituted by growing sun hemp (*Crotolaria juncea*) in the interspaces of coconut (Jacob 2004). Cultivation of *Gliricidia sepium* as green manure is also a practical method of increasing fertility in the islands. Further, selection of high-yielding palm varieties is also very important to improve productivity. Cultivation of MPTs such as *Moringa oleifera* and fruits like banana, papaya and watermelon and tuber crops, mushroom and vegetables has been found profitable. Kumar and Nair (2004) and Dagar et al. (2014, 2020) have given a detailed account of homegardens of Kerala state. These are common landscape in and around most of the cities in the state.

4.5.3 Improving Livelihoods, Food and Nutritional Security

Renewable fuels represent 7% of the total fuel in the world but biomass represents 70% of household consumption in developing countries and 50% of total fuel consumption in Africa alone (FAO 2007). In Africa as a whole, the fuelwood value chain contributes more than 80% of all the household fuel consumed and it is forecasted that Africa is the only continent where the use of fuelwood for household purposes (especially in towns) will be growing in coming decades

(FAO 2012). Fuelwood supplies for towns often come from deforestation of peri-urban forests. Agroforestry systems have the potential not only to minimize the pressure on peri-urban forests for fuelwood but also meeting the requirement of nutrition and food as has been already explained in text. Trees like *Moringa oleifera* (leaves and fruits rich in all minerals and vitamins), *Emblica officinalis* (medicinal and rich in vitamin C), species of *Citrus* (rich in vitamin C and minerals), many other fruits and vegetables, grasses and legumes (fodder), coarse grain cereals in dry regions and animals and several local tree species (depending upon climate) constitute different agroforestry practices which enhance livelihood security.

4.5.4 Adaptation to Climate Vulnerability

It is established fact that comparative to other land uses agroforestry is a better adaptation for land use system tolerant to stress (biotic, climatic, salinity, waterlogging, etc.) to mitigate climate-related risks (Dagar et al. 2012, 2016a, b). Agroforestry trees improve soil (fertilizer trees) fertility, protect associated crop (wind breaks, live fence) and improve micro-environment. On one study, Venkateswarlu and Singh (2015) carried out in CRIDA Hyderabad (India) indicated that there will be 7% increase in crop water requirement by 2050 across all locations; therefore, domestication of food yielding low water-requiring halophytic crops in agroforestry mode will be useful. Choice of plantation crops is also important. Naresh-Kumar and Aggarwal (2013) reported that under present management status, climate change (increase in temperature) may increase (4.3–6.8%) coconut productivity in coastal regions of India. Agronomic adaptations such as soil moisture conservation, summer drip irrigation and fertilizer management can further increase the yield of coconut-based systems. Genetic adaptation measures like growing improved local tall cultivars and hybrids under improved management are needed for long-term adaptations, which can increase 25–32% yield in 2080 climate scenario (Naresh-Kumar 2015; Naresh Kumar et al. 2020).

Urban development in itself can also increase the risk of natural disasters and vulnerability of populations. The increase in impervious surfaces associated with urban development can reduces soil infiltration rates and increase runoff during storms resulting in flooding, particularly where drainage systems are lacking (Matagi 2002). In Africa, the problems of development-induced flooding are widely reported in the cities of Ibadan, Kampala, Dakar, Douala, Nairobi and Addis Ababa (Action Aid 2006; Douglas et al. 2008). Urban expansion and residential development often occurring in steep slopes can increase the risk of landslide hazards associated with increased frequency of rainfall events. Many coastal cities are also seeing unprecedented effects of global environmental change. Coastal inundation during extreme events and Tsunamis is now a familiar phenomenon.

Landslide hazards can be mitigated by UPAF through stabilization of steep slopes where urban expansion and residential development often occur (Matagi 2002). UPAF has demonstrated flood reduction capabilities in Accra, Kampala and Dar es Salaam by extending the time lag between floods and the slowing of storm waters. Reduction of surface runoff ranges between 15% and 20% of rainfall depending on city surface condition, soil composition and permeability (Dubbeling et al. 2009). In the case of coastal flooding, agroforestry has contributed to the reduction of coastal inundation during extreme events, for example, the cultivation of mangrove agroforests in Doula (Walters et al. 2008). In addition to reducing runoff, more porous land surfaces support recharge of water tables and increase groundwater flows. Therefore, developing stress-tolerant crops, domestication of halophytes and better management practices in agroforestry mode will be helpful in adaptation to climate change, urban and peri-urban agroforestry will be no exception.

4.5.5 Climate Change Mitigation

The contribution of the agroforestry systems including in urban areas to mitigate the climate change through increased above-ground soil carbon stock is appreciable, and many studies suggested higher amount of sequestration potential of agroforestry systems (Newaj et al. 2020). Evidence associated with this type of system and pathway suggests a high potential for mitigation of climate change if scaled up to city-regional level. Evidence exists around agriculture's potential in sequestering CO_2. Comparing with other systems, the capacity to trap the carbon is in the order of forests > agroforestry > tree plantation > arable crops and different levels of canopy and plant species in the agroforestry help to trap more carbon than the homogenous crops in the field (Nair et al. 2009). Fast-growing trees such as *Eucalyptus* plantation can play an important role as carbon sinks and contribute significantly to the removal of CO_2 from the atmosphere. In one study, 10-year-old plantation of *E. tereticornis* (520 trees per ha) irrigated with sewage water sequestered 351 Mg ha^{-1} carbon showing its potential in carbon sequestration (Minhas et al. 2015). Forestry and agroforestry systems also provide safer outlet for disposal of urban wastewater because of high transpiration rates. The organic matter and nutrients present in the wastewater fasten the plant growth and also stimulate microbial population which further helps to fasten the trapping process and result in higher C sequestration and other environmental benefits. Compared to groundwater, sewage-irrigated 10-year-old Eucalyptus plantation absorbed 7% more total C removed (Minhas et al. 2015). About 61–71% of the total C absorbed (including below ground) and more than 90% of the above-ground C absorption were contributed by the Eucalyptus bole, whereas contribution of below-ground biomass ranged between 23% and 33% of the total C stock (Lal et al. 2020).

The carbon absorption by tree plantations in a given area varies with plantation age corresponding to variations in growth as well as plantation density. Minhas et al. (2015) recorded total C stocked in 10-year-old sewage-irrigated *Eucalyptus tereticornis* plantations to be 38.6, 121.9, 156.1 and 153.7 Mg h ha^{-1} with the annual carbon absorption of 3.5, 12.0, 13.9 and 7.0 Mg ha^{-1} in low (163 stems ha^{-1}), recommended (517 stems ha^{-1}), high (1993 stems ha^{-1}) and very high (6530 stems ha^{-1}) stocking density, respectively. Fernández-Núñez et al. (2010) also recorded similar observations in 11-year-old plantation of *Pinus radiata* on acidic soils of Spain and the C sequestered by the plantation (1667 trees ha^{-1}) was increased from 4.09 Mg C ha^{-1} when no fertilizer was applied to 7.0 Mg C ha^{-1} when sewage sludge was used as fertilizer in the same soil. Mosquera-Losada et al. (2010) also reported that the addition of sewage sludge increased SOM content through the input of organic matter as well as calcium via the sewage sludge.

At one site in Indo-Gangetic plains, the agroforestry system based on *Populus deltoides* has been developed on an intensively managed agriculture farm of about 40 ha, which is fully mechanized and partially irrigated with treated diluted sewage water. Carbon pool in aboveground biomass of trees in the agroforestry system (29–44 Mg C ha^{-1}). The allocation of carbon to belowground components amounted to 6.27–9.51 Mg C ha^{-1}. The carbon pool in soil varied from 16 to 22 Mg C ha^{-1} up to 30 cm soil depth (Gaur and Gupta 2012).

4.5.6 Utilization of Wastewaters in Urban and Peri-Urban Agroforestry

The use of tree plantations continues to be investigated globally for sustainable disposal or re-use of wastewater, improving livelihood security of millions small holders, impact on soil fertility, phytoremediation, soil reclamation, creation of wetlands for improving biodiversity, environmental services and potential as a climate change adaptation measure.

According to FAO's Aquastat database, only 52% of the municipal wastewater produced globally is recycled (FAO 2011). Many developing countries have inadequate systems for treating wastewater, and there is a lack of sewage networks and wastewater treatment plants. Therefore, the use of treated wastewater in forestry and agroforestry should be integrated into urban and peri-urban areas, where it can contribute to the greening of landscapes and help support local farmers in the production of goods and environmental services. Some wastewater safety measures are summarized as follows:

- Wastewater to be used for agriculture and forestry should be treated to at least the secondary level to avoid the risk that foresters and farmers, and consumers of harvested products,
- Secondary-treated water can be used for certain agroforestry crops for the production of fodder and woody crops (but it cannot be used for horticultural irrigation).
- Tree irrigation with treated wastewater can be implemented close to human settlements in urban and peri-urban areas; reduces the cost of pumping.
- Constructed wetlands are cost-effective, affordable, produce secondary-treated water suitable for agroforestry systems and tree plantations to produce cash crops, reduce (or prevent) soil erosion, and provide windbreaks, shade and fodder. Lack

of knowledge and experience in the use of constructed wetlands. There is a need to collect real data for chemical modelling of pollutant removal.

4.6 Research and Policy Issues

- There is need to develop affordable techniques of UPAF systems by identifying the suitable economically viable plant species and crops for different systems and use of different qualities of water such as (a) untreated wastewater, (b) partial treated sewage water, (c) treated and harvested rainwater and (d) conjunctive use of water.
- Need to develop quality standards for different uses of wastewaters of different types based on their source of generation, extent of treatments and the kind of agricultural systems involving agroforestry and also need to develop low-cost and user- and environment-friendly techniques for wastewater treatments and develop model systems.
- Designing cost effective structures for different systems; standardization of plant nutrients of different crops; optimum water needs in different systems; plant protection issues; harvest index and harvesting tools; packing, transportation and storage; marketing; and health and social issues.
- Proper irrigation methods such as drip irrigation for different systems must be developed. Cheap techniques such as passing the sewage water without heavy metal loads through gravel media or specially designed vegetation-beds or bio-absorbents may be passed before its use for irrigation or simple sedimentation or bio-sedimentation and solar techniques may be used.
- Issues like land tenure, availability of land for agroforests, integration of related government-schemes with UPAF programmes, understanding, collaboration and skill development of different stakeholders, funding from government and out-side government sources, value addition, accessibility to market and issues such as carbon credit and insurance of agroforestry-related crops in peri-urban areas must be part of policy at state and country level.

References

Action Aid (2006) Climate change, urban flooding and the rights of the urban poor in Africa: key findings from six African countries. Action Aid, London

Akinnifesi FK, Sileshi GW, Ajayi CO, Akinnifesi AI, de Moura EG, Linhares JFP, Rodrigues I (2010) Biodiversity of urban homegardens of Sao Luis city, northeastern, Brazil. Urban Ecosyst 13:129–146

Aronson MF, La Sorte FA, Nilon CH, Katti M, Goddard MA, Lepczyk CA, Warren PS, Williams NS, Cilliers S, Clarkson B, Dobbs C, Dolan R, Hedblom M, Klotz S, Kooijmans JL, Kühn I, Macgregor-Fors I, McDonnell M, Mörtberg U, Pysek P, Siebert S, Sushinsky J, Werner P, Winter M (2014) A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proc Biol Sci 281:20133330. https://doi.org/10.1098/rspb.2013.3330

Borelli S, Cnigliaro M, Quaglia S, Salbitano F (2017) Urban and peri-urban agroforestry as multi-functional land use. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 705–724

Brandis D (1897) Indian forestry. Oriental Institute, Poona

Brown LR (2001) Eco-economy: building an economy for the earth. Norton, New York

Bryld E (2003) Potentials, problems, and policy implications for urban agriculture in developing countries. Agric Hum Values 20:79–86

Bukowski C, Munsell J (2018) The community food forest handbook: how to plan, organize, and nurture edible gathering places. Green Pub, Chelsea

Cadenasso ML, Pickett STA (2013) Three tides: the development and state of the art of urban ecological science. In: Pickett ST, Cadenasso ML, McGrath B (eds) Resilience in ecology and urban design: linking theory and practice for sustainable cities. Springer, Dordrecht, pp 29–46

Census Commissioner's Office, India (1894) Census of India, vol. 33, Report on the census of Travancore, taken by command of his highness the Maharajah on the 26 February 1891, London, UK

Chadwick LC (1971) 3000 years of arboriculture: past, present and the future. Arborists News 36(6):73–78

Chakeredza S, Hove L, Akinnifesi FA, Franzel S, Ajayi O, Sileshi G (2007) Managing fodder trees as a solution to human-livestock food conflicts and their contribution to income generation for smallholder farmers in Southern Africa. Nat Res Forum 31:286–291

Crist E, Mora C, Engelman R (2017) The interaction of human population, food production, and biodiversity protection. Science 356:260–264

CWC (2010) Water and related statistics. Water Planning and Project Wing, Central Water Commission, India

DAC (2011) Guidelines for the vegetable initiative for urban clusters. Department of Agriculture & Cooperation, Ministry of Agriculture, Govt. of India, p. 14

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh A, Arunachalam A (eds) Agroforestry systems in India: livelihood security & environmental services, advances in agroforestry, vol 10. Springer, Dordrecht, pp 273–332

Dagar JC, Minhas PS (2016) Agroforestry to rehabilitate the Indian coastal saline areas. In: Dagar JC, Minhas PS (eds) Agroforestry for management of waterlogged saline soils and poor-quality waters. Advances in agroforestry series, vol 13. Springer, New Delhi, pp 121–143

Dagar JC, Tewari VP (2017) Evolution of agroforestry as a modern science. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 13–90

Dagar JC, Singh AK, Singh R, Arunachalum A (2012) Climate change vis-à-vis Indian agriculture. Ann Agric Res 33(4):189–203

Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & environmental services, advances in agroforestry, vol 10. Springer, New Delhi, pp 185–232

Dagar JC, Lal K, Jeet-Ram M-K, Yadav RK, Chaudhari SK, Sharif-Ahamad SG, Kaur A (2016a) Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in north-west India. Agric Ecosyst Environ 233:33–42

Dagar JC, Sharma PC, Chaudhari SK, Jat HS, Ahamad S (2016b) Climate change vis-a-vis saline agriculture: impact and adaptation strategies. In: Dagar JC, Sharma PC, Sharma DK, Singh AK (eds) Innovative saline agriculture. Springer, New York, pp 5–53

Dagar JC, Gangaiah B, Gupta SR (2020) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1. Springer, Singapore, pp 367–424

De Bon H, Parrot L, Moustier P (2010) Sustainable urban agriculture in developing countries. a review. Agron Sustain Dev 30:21–32
De Zeeuw H, Van Veenhuizen R, Dubbeling M (2011) The role of urban agriculture in building resilient cities in developing countries. J Agric Sci 149:153
Despomier D (2018) Vertical farming using hydroponics and aquaponics. In: Lal R, Stewart BA (eds) Urban soils. CRC Press, Boca Raton, pp 313–327
Despommier D, Carter M (2011) The vertical farm: feeding the world in the 21st century, Picador UK
Dessler AE, Parson EA (2019) The science and policies of global climate change, 3rd edn. Cambridge University Press, Cambridge
Di Leo N, Escobedo FJ, Dubbeling M (2016) The role of urban green infrastructure in mitigating land surface temperature in Bobo-Dioulasso, Burkina Faso. Environ Dev Sustain 18:373–392
Douglas I, Alam K, Maghenda M, Mcdonnell Y, Mclean L, Campbell J (2008) Unjust waters: climate change, flooding and the urban poor in Africa. Environ Urban 20:187–205
Drescher AW, Holmer RJ, Iaquinta DL (2006) Urban homegardens and allotment gardens for sustainable livelihoods: management strategies and institutional environments. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time tested example of sustainability. Springer, Dordrecht, pp 317–338
Dubbeling M, Caton Campbell M, Hoekstra F, Van Veenhuizen R (2009) Editorial: building resilient cities. Urban Agric Mag 2009:3–11
Duguma LA, van Noordwijk M, Minang PA, Muthee K (2021) COVID-19, pandemic and agroecosystem resilience: early insights for building better futures. Sustain For 13:1278. https://doi.org/10.3390/su13031278
Escobedo FJ, Kroeger T, Wagner JE (2011) Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ Pollut 159:2078–2087
FAO (2001) Urban and peri urban agriculture - a briefing guide for the successful implementation of urban and peri-urban agriculture in developing countries and countries of transition. Food and Agriculture Organization of United Nations, Rome
FAO (2007) Profitability and sustainability of urban and peri-urban agriculture. FAO, Rome
FAO (2009) Food, agriculture and cities: challenges of food and nutrition security, agriculture and ecosystem management in an urbanizing world. FAO, Rome, p 45
FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW) – managing systems at risk. Food and Agriculture Organization of the United Nations, Rome
FAO (2012) On-farm practices for the safe use of wastewater in urban and peri-urban horticulture: a training handbook for farmer field schools. Food and Agricultural Organisation of the United Nations, Rome
FAO/UNESCO (1990) Soil map of the world: revised legend with corrections and updates. World soil resource report 60. FAO, Rome
Fernández-Núñez E, Rigueiro-Rodríguez A, Mosquera-Losadaa MR (2010) Carbon allocation dynamics one decade after afforestation with Pinus radiata under two stand densities in NW Spain. Ecol Eng 36:876–890
Galhena DH, Freed R, Maredia KM (2013) Home gardens: a promising approach to enhance household food security and wellbeing. Agric Food Secur 2(1):8. https://doi.org/10.1186/2048-7010-2-8
Gallaher CM, Kerr JM, Njenga M, Karanja NK, WinklerPrins AM (2013) Urban agriculture, social capital, and food security in the Kibera slums of Nairobi, Kenya. Agric Hum Values 30:389–404
Gaur A, Gupta SR (2012) Impact of agroforestry systems on carbon sequestration in Northern Haryana, India. Int J Ecol Environ Sci 38(2):73–85
Global Footprint Network (2014) Global footprint network annual report 2014. www.footprintnetwork.org
Goettsch B, Urquiza-Haas T, Koleff P, Acevedo Gasman F, Aguilar-Meléndez A, Alavez V, Alejandre-Iturbide G, Aragón Cuevas F, Azurdia Pérez C, Carr JA, Castellanos-Morales G, Cerén G, Contreras-Toledo AR, Correa-Cano ME, De la Cruz LL, Debouck DG, Delgado-

Salinas A, Gómez-Ruiz EP, González-Ledesma M, Jenkins RKB (2021) Extinction risk of Mesoamerican crop wild relatives. Plants People Planet 2021:10225
Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008a) Global change and the ecology of cities. Science 319(5864):756–760. https://doi.org/10.1126/science.1150195
Grimm NB, Foster D, Groffman P, Grove JM, Hopkinson CS, Nadelhoffer KJ et al (2008b) The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. Front Ecol Environ 6:264–272
Grimmond S (2007) Urbanization and global environmental change: local effects of urban warming. Geogr J 173:83–88
Hamilton AJ, Burry K, Mok HF, Barker SF, Grove JR, Williamson VG (2014) Give peas a chance? Urban agriculture in developing countries. A review. Agron Sustain Dev 34:45–73
Hart R (1996) Forest gardening: cultivating an edible landscape. White River Jct. Chelsea Green, Vermont
Hemmelgarn HL, Munsell JF (2021) Exploring 'beyond-food' opportunities for biocultural conservation in urban forest gardens. Urban Agric Region Food Syst 6:e220009. https://doi.org/10.1002/uar2.20009
IPCC (2007) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 996
IPCC (2014) Summary for policymakers. In: Field CB (ed) Climate change 2014: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, pp 1–32
IPCC (2021) Summary for policymakers. In: Delmotte M et al (eds) Climate change 2021: the physical science basis. Cambridge University Press, Cambridge
IUCN (2020) The IUCN red list of threatened species. www.iucnredlist.org
Jacob PM (2004) Strategies for enhancing production and productivity in the coastal ecosystem of Lakshadweep Islands. J Indian Soc Coast Agric Res 22:152–155
Karesh WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, Aldrich S, Harrington T, Formenty P, Loh EH (2012) Ecology of zoonoses: natural and unnatural histories. Lancet 380:1936–1945
Knorr D, Khoo CSH, Augustin MA (2018) Food for an urban planet: challenges and research opportunities. Front Nutr 4:73. https://doi.org/10.3389/fnut.2017.00073
Koninjnendijk C, Gauthier M (2006) Urban forestry for multifunctional urban land use. In: Van Leusden VR (ed) City farming for the future: urban agriculture for green and productive cities. International Development Research Centre, Ottawa, pp 411–442
Kumar BM (2011) Species richness and aboveground carbon stocks in the homegardens of central Kerala, India. Agric Ecosyst Environ 140:430–440. https://doi.org/10.1016/j.agee.2011.01.006
Kumar BM, Nair PKR (2004) The enigma of tropical homegardens. Agrofor Syst 61:135–152
Kumar BM, George SJ, Chinnamani S (1994) Diversity, structure and standing stock of wood in the homegardens of Kerala in peninsular India. Agrofor Syst 25:243–262
La Rosa D, Barbarossa L, Privitera R, Martinico F (2014) Agriculture and the city: a method for sustainable planning of new forms of agriculture in urban contexts. Land Use Policy 41:290–303
Lal R (2020) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Secur 12:871–876
Lal K, Franco D, Rosin KG, Yadav RK (2020) Urban and peri-urban agroforestry: utilization of wastewater and degraded landscapes for environmental and livelihood security. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges. Springer, Singapore, pp 253–295
Laurance WF, Engert J (2022) Sprawling cities are rapidly encroaching on Earth's biodiversity. Proc Natl Acad Sci U S A 119:e2202244119. https://doi.org/10.1073/pnas.2202244119
Lee-Smith D (2010) Cities feeding people: an update on urban agriculture in equatorial Africa. Environ Urban 22:483–499

Lee-Smith D, Prain G (2006) Understanding the links between agriculture and health. Focus 13. International Food Policy Research Institute, Washington

Lentz DL, Dunning NP, Scarborough VL, Magee KS, Thompson KM, Weaver E, Carr C, Terry RE, Islebe G, Tankersley KB, Grazioso Sierra L, Jones JG, Buttles P, Valdez F, Ramos HCE (2014) Forests, fields and the edge of sustainability at the ancient Maya city of Tikal. PNAS 111(52): 18513–18518

Lin BB, Egerer MH (2018) Urban agriculture: an opportunity for biodiversity and food provision in urban landscapes. In: Ossola A, Niemela J (eds) Urban biodiversity: from research to practice. Routledge, London, pp 71–86

Lin BB, Philpott SM, Jha S (2015) The future of urban agriculture and biodiversity-ecosystem services: challenges and next steps. Basic Appl Ecol 16:189–201. https://doi.org/10.1016/j.baae.2015.01.005

Logan W (1906) Malabar manual, 2nd edn. Asian Education Services, Madras, p 772

Lovell ST (2010) Multifunctional urban agriculture for sustainable land use planning in the United States. Sustain For 2:2499–2522. https://doi.org/10.3390/su2082499

Lovell ST, Taylor JR (2013) Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc Ecol 28:1447–1463

Lwasa S, Mugagga F, Wahab B, Simon D, Connors JP, Griffith C (2015) A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. Curr Opin Environ Sustain 13:68–73. https://doi.org/10.1016/j.cosust.2015.02.003

Malhotra KC (1998) Anthropological dimensions of sacred groves in India: an overview. In: Ramakrishnan PS, Saxena KG, Chandrasekara UM (eds) Conserving the sacred for biodiversity management. New Delhi, IBH, pp 423–438

Mann HS, Saxena SK (1980) Khejri *(Prosopis cineraria*) in the Indian desert: its role in agroforestry. CAZRI, Jodhpur

Matagi SV (2002) Some issues of environmental concern in Kampala, the capital city of Uganda. Environ Monit Assess 77:121–138

Mateer S (1883) Native life in Travancore. WH Allen & Co., London, p 450

Mbow C, Van Noordwijk M, Prabhu R, Simons T (2014) Knowledge gaps and research needs concerning agroforestry's contribution to sustainable development goals in Africa. Curr Opin Environ 6:162–170

McCarthy H (1993) Managing oaks and the acorn crop. In: Thomas CB, Anderson K (eds) Before the wilderness: environmental management by native Californians. Ballena Press, Banning

McDougall R, Kristiansen P, Rader R (2019) Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve sustainability. Proc Natl Acad Sci U S A 116(1):129–134

Menefee DS, Hettiarachichi GM (2018) Contaminants in urban soils: biodiversity and transfer. In: Lal R, Stewart BA (eds) Urban soils. CRC Press, Boca Raton, pp 175–187

Merriam CH (1918) The Acorn, a possibly neglected source of food. Natl Geogr Mag 34(2): 129–137

Miller RW (2004) Urban forestry: history and introduction. In: Konijnendijk CC, Schipperijn J, Hoyer KK (eds) Forestry serving urbanised societies. Selected papers from a conference jointly organized by IUFRO, EFI and the Danish Centre for Forest, Landscape and Planning-KVL in Copenhagen, Denmark, 27-30 August 2002, Vienna, IUFRO, 2004-p407 (IUFRO world Series vol 14)

Minhas PS, Yadav RK, Lal K, Chaturvedi RK (2015) Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (*Eucalyptus tereticornis* Sm.) planted at variable stocking density. Agric Water Manag 152:151–160

Montagnini F (2006) Homegardens of Mesoamerica: biodiversity, food security, and nutrient management. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time-tested example of sustainable agroforestry. Springer, Dordrecht, pp 61–84

Moraga VD (1996). An eternity of forest – paintings by Mbuti women. essay and introduction to the exhibition, Berkeley Art Museum, Berkeley, California, USA

Mosquera-Losada MR, Muñoz-Ferreiro N, Rigueiro-Rodríguez A (2010) Agronomic characterisation of different types of sewage sludge: policy implications. Waste Manag 30(3):492–503
MSSRF (2010) Report on the state of food insecurity in urban India. M.S Swaminathan Research Foundation (MSSRF), Chennai
NAAS (2022) Utilization of wastewater in urban and peri-urban agriculture. Policy Paper No 106. National Academy of Agricultural Sciences, New Delhi, p 26
Nair PKR (1993) An introduction to agroforestry. Kluwer Academic Publishers, Dordrecht
Nair PK (2007) The coming of age of agroforestry. J Sci Food Agric 87(9):1613–1619
Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23
Naresh Kumar S, Chander S, Sinha P, Padaria RN (2020) Climate change impact, vulnerability and adaptation: agriculture. A report for India's Third National Communication to UNFCCC
Naresh-Kumar S (2015) Carbon sequestration and beyond by plantations: exploring scope for added income. In: Dhyani SK, Newaj R, Alam B, Dev I (eds) Agroforestry: present status and way forward. Biotech Books, New Delhi, pp 193–205
Naresh-Kumar S, Aggarwal PK (2013) Climate change and coconut plantations in India: impacts and potential adaptation gains. Agric Syst 117:45–54
Newaj R, Chaturvedi OP, Kumar D, Chavan SB, Rajawat BS, Yadav DK (2020) Carbon sequestration potential of agroforestry systems in rehabilitating degraded lands in India. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes-Recent advances and emerging challenges, vol 2. Springer, Singapore, pp 319–348
Odurukwe S (2004) Agroforestry in Peiurban cities of Abia State, Nigeria. In: Urban agriculture magazine, no 13. RUAF, Leusden
Orsini F, Kahane R, Nono-Womdim R, Gianquinto G (2013) Urban agriculture in the developing world. A review. Agron Sustain Dev 33:695–720
Orsini F, Pennisi G, Michelon N, Minelli A, Bazzocchi G, Sanyé-Mengual E, Gianquinto G (2020) Features and functions of multifunctional urban agriculture in the global north: a review. Front Sustain Food Syst 4:562513. https://doi.org/10.3389/fsufs.2020.562513
Pickett STA, Cadenasso ML, Childers DL, McDonnell MJ, Zhou W (2016) Evolution and future of urban ecological science: ecology in, of, and for the city. Ecosys Health Sustain 2(7):01229
Poulsen MN, McNab PR, Clayton ML, Neff RA (2015) A systematic review of urban agriculture and food security impacts in low-income countries. Food Policy 55:131–146
Prain G, Karanja N, Lee-Smith D (2010) African urban harvest: agriculture in the cities of Cameroon, Kenya and Uganda. Springer, New York
Randhawa MS (1980) A history of Indian agriculture: eighth to eighteenth century, vol 2. New Delhi, Indian Council of Agricultural Research, p 358
Rao P (1996) Sacred groves and conservation. WWF India Q 7:4–8
Raychaudhuri SP, Roy M (1993) Agriculture in ancient India. ICAR, New Delhi
Salbitano F, Borelli S, Sanesi G (2015) Urban forestry and agroforestry. In: de Zeuuw H, Drechsel P (eds) Cities and agriculture: developing resilient urban food systems. Earthscan, London, pp 285–311
Sato T, Manzoor Q, Sadahiro Y, Tsuneyoshi E, Zahoor A (2013) Global, regional, and country level need for data on wastewater generation, treatment, and use. Agric Water Manag 130:1–13
Shackleton CM, Cilliers SS, du Toit MJ, Davoren E (2021) The need for an urban ecology of the global south. In: Shackleton CM, Davoren E, Cilliers SS, du Toit MJ (eds) Urban ecology in the global south. Springer, Cham, pp 1–26
Shochat E, Warren PS, Faeth SH, McIntyre NE, Hope D (2006) From patterns to emerging processes in mechanistic urban ecology. Trends Ecol Evol 21:186–191
Simkin RD, Seto KC, McDonald RI, Jetz W (2022) Biodiversity impacts and conservation implications of urban land expansion projected to 2050. Proc Natl Acad Sci U S A 119(12): e2117297119. https://doi.org/10.1073/pnas.2117297119
Singh HP, Malhotra SK (2013) Urban and peri-urban horticulture for greening the cities, utilizing the waste, meeting the needs and servicing the environment. In: Sumangla HP, Malhotra SK,

Chowdappa P (eds) Urban and peri-urban horticulture- a perspective. Conf Hort Assoc, New Delhi, pp 1–11

Sloan S, Jenkins CN, Joppa LN, Gaveau D, Laurance WF (2014) Remaining natural vegetation in the global biodiversity hotspots. Biol Conserv 177:12–24

Sperling CD, Lortie CJ (2010) The importance of urban backgardens on plant and invertebrate recruitment: a field microcosm experiment. Urban Ecosyst 13:223–235. https://doi.org/10.1007/s11252-009-0114-y

Ul-Allah S, Khan AA, Burkert A, Wachendor M (2014) Socio-economic aspects of fodder production in urban and peri-urban areas of Faisalabad. Pak J Agric Sci 51(2):483–490

UN (2018) The world's cities in 2018—data booklet (ST/ESA/ SER.A/417). United Nations, Department of Economic and Social Affairs, Population Division. https://www.un.org/en/events/citiesday/assets/pdf/the_worlds_cities_in_2018_data_booklet.pdf

UNEP (2016) GEO-6 regional assessment for Asia and the Pacific. United Nations Environment Programme, Nairobi

UNEP (2021) Cities and climate change. https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/cities-and-climate-change. Accessed 10 February 2021

UN-Habitat (2014) The state of African cities 2014: re-imaging sustainable urban transition. Human Settlement Program, Nairobi

Vajpeyi Y (2000) Tree of life. Indian Express (Sunday Magazine), India

Valenzuela H (2016) Agroecology: a global paradigm to challenge mainstream industrial agriculture. Horticulturae 2:2

Van Leeuwen B (2010) Dealing with urban diversity: promises and challenges of city life for intercultural citizenship. Polit Theor 38(5):631–657

Venkateswarlu B, Singh AK (2015) Climate change adaptation and mitigation strategies in rainfed agriculture. In: Singh AK, Dagar JC, Arunachalam A, Gopichandran R, Shelat KN (eds) Climate change modelling, planning and policy for agriculture. Springer, Cham, pp 1–12

Walters B, Ronnback P, Kovacs J, Crona B, Hussain S, Badola R, Primavera JH, Barbie E, Dahdouh-Guebas F (2008) Ethnobiology, socio-economics and management of mangrove forests: a review. Aquat Bot 89(2):220–236

WHO (2002) WHO monograph on selected medicinal plants, vol 2. World Health Organisation, Geneva

Wortman SE, Lovell ST (2013) Environmental challenges threatening the growth of urban agriculture in the United States. J Environ Qual 42:1283–1294. https://doi.org/10.2134/jeq2013.01.0031

Wu J (2008) Making the case for landscape ecology: an effective approach to urban sustainability. Landsc J 27:41–50

Wu J (2014) Urban ecology and sustainability: the state-of-the-science and future directions. Landsc Urban Plan 125:209–221

Part II
Landscape Restoration and Combating Desertification

Chapter 5
Agroforestry for Climate Change Resilience in Degraded Landscapes

Sharda Rani Gupta, Jagdish Chander Dagar, Gudeta Weldesemayat Sileshi, and R. K. Chaturvedi

Abstract Agriculture constitutes the largest economic sector in Asia and Africa; therefore, issues like land degradation, food security, biodiversity loss and climate change are inextricably linked with sustainable agricultural production. Land degradation due to expansion of croplands and grazing lands, deforestation and soil erosion are the most pressing problems across Asia and Africa. Warming trends and increasing climate extremes are of common occurrence threatening food security and human well-being. The UN Decade on Ecosystem Restoration (2021–2030) aims to halt the degradation of ecosystems, and to enhance livelihoods, counteract climate change and biodiversity loss. Land restoration initiatives ranging from small local projects to large-scale programmes are being implemented for restoring degraded landscapes. Agroforestry constitutes as an important approach to restore degraded land by re-establishing ecological processes, structures and ecosystem functions. Agroforestry systems, integrating trees, crops and livestock, involve diverse land management practices like crop diversification, long rotation systems for soil conservation, home gardens, boundary plantings, perennial crops, hedgerow intercropping, live fences and improved fallows for enhancing their resilience to climate change. Agroforestry provides climate resilience through diversification of agricultural production, reducing the risk of crop failure and food shortages, improvement of microclimate, increase intensive silvopastoral systems, facilitating

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capture and storage of carbon in plant biomass and soil, controlling soil erosion and improving soil fertility. This chapter reviews a number of studies and demonstrates that agroforestry systems can substantially increase C sequestration within tree biomass and soils. In Sub-Saharan Africa, AFS and integrated land use could sequester about 0.50–3.9 Mg C ha^{-1} $year^{-1}$ C in the biomass and the total carbon stock in agroforestry systems averaged 15.7–77.9 Mg C ha^{-1}. Total carbon storage potential in Southeast Asian agroforestry systems was in the range of 46.8–209 Mg C ha^{-1}. In addition, agroforestry practices play a key role for adaptation under changing climate conditions.

Keywords Degraded landscapes · Climate change · Ecosystem restoration · Resilience · Ecosystem services · Resource efficiency · Drivers · Carbon sequestration · Mitigation · adaptation

5.1 Introduction

In an era of global environmental change, Asian and African countries are experiencing large-scale land and seascapes degradation, and unprecedented climate change, biodiversity loss and chemical pollution. Many developing countries, especially Asia and Africa, are vulnerable to climate change, which is impacting agricultural production and livelihood options of people. Land degradation has become a critical issue worldwide, especially in the developing countries, which face great concerns about food security (FAO and ITPS 2015). Food security is being constrained by persistent land degradation due to deforestation and poor agricultural practices leading to heavy soil erosion, salinization, land fragmentation, intensive cultivation, labour problem and over-exploitation of natural resources (FAO and ITPS 2015; IPBES 2018). Climate change has been predicted to have varying effects on the expression of land degradation, salinity, waterlogging and inundation in landscapes. Land degradation threatens food security, fuels violent conflict, drives biodiversity loss and contributes to the climate crisis through the emission of greenhouse gases. About 40% of the land on the African continent (65% of arable land, 30% of grazing land and 20% of forest land) is under serious degradation due to soil erosion, soil nutrient depletion, soil organic matter decline and associated soil biodiversity loss (FAO and ITPS 2015). Water erosion is the major type of erosion in South and East Asia with alternating dry and wet seasons, whereas wind is the key driving force inducing soil erosion in the drylands and desert areas both in Asia and Africa (FAO and ITPS 2015). Land degradation through human activities is adversely impacting the well-being of at least 3.2 billion people globally (IPBES 2018) and indirectly affects them through the loss of biodiversity and ecosystem services at a cost exceeding 10% of the annual global gross production (IPBES 2018). Avoiding, reducing or reversing land degradation is essential for achieving many of the Sustainable Development Goals (SDGs) by 2030.

Agroforestry is becoming increasingly important because of its ability to restore degraded landscapes (Dagar and Minhas 2016; Dagar and Singh 2018; Dagar et al. 2020a, b; Kuyah et al. 2019; Dagar and Gupta 2020), and its multiple roles and ecosystem services including biodiversity conservation (McNeely and Schroth 2006; Udawatta et al. 2017; Santos et al. 2019), carbon sequestration (de Stefano and Jacobson 2018; Nath et al. 2021; Ramos et al. 2018), adaptation and mitigation of climate change (Duguma et al. 2015; Mbow et al. 2014a, b; van Noordwijk 2019; van Noordwijk et al. 2019a, b, c) and providing livelihood security to people (Dagar et al. 2014a, b; Hillbrand et al. 2017). The IPCC's special report on climate change and land degradation highlighted that agroforestry was one of the best options to address climate change mitigation, climate change adaptation, land degradation, desertification and food security at the same time (IPCC 2019a, b). The adoption of agroforestry can mitigate costs associated with climate change while enhancing local adaptation (Lin et al. 2021). The objective of this chapter is to provide an overview of land degradation and restoration challenges for Asia and Africa, impact of the climate variability and the role of agroforestry in building resilience to climate change in degraded landscapes.

5.2 Land Degradation and Restoration Challenge

5.2.1 Extant of Land Degradation

Although land degradation has been a critical problem throughout history (Diamond 2005), it has become a major global issue since the second half of the twentieth century (Nkonya et al. 2011). Rapid expansion and unsustainable management of croplands and grazing lands, deforestation, besides global consumption patterns and climate change are the main direct drivers of land degradation (Sutton et al. 2016; UNCCD 2017b), causing significant reduction in productivity and loss of biodiversity and ecosystem services. Other contributory factors to degradation include urbanization, infrastructure development, faulty methods of agriculture and landscape modifications through extractive industries (UNCCD 2017a). Land degradation is a complex issue which involves both the natural ecosystem and the socioeconomic system. It refers to the many processes that drive the decline or loss in biodiversity, ecosystem functions or services and this includes the degradation of all terrestrial ecosystems (IPBES 2018).

Processes of land degradation are those direct mechanisms by which land is degraded and are similar to the notion of 'direct drivers' in the Millennium Ecosystem Assessment Framework (MEA) (2005). The IUCN report has analysed the drivers and pressures of land degradation using the Drivers-Pressure-State-Impact-Response (DPSIR) model as shown in Fig. 5.1. In this model, the underlying or root causes of land degradation are termed 'Drivers', whereas the direct causes are termed 'Pressures'. The 'Drivers' or underlying causes of land degradation can be grouped into two categories: those due to natural causes, conditions and biophysical processes, such as intrinsic land quality, climatic variables and soil biodiversity and others related to human society, such as poverty, demographic change, and economic and political factors (Solh 2009; Eswaran et al. 2001); examples of the latter

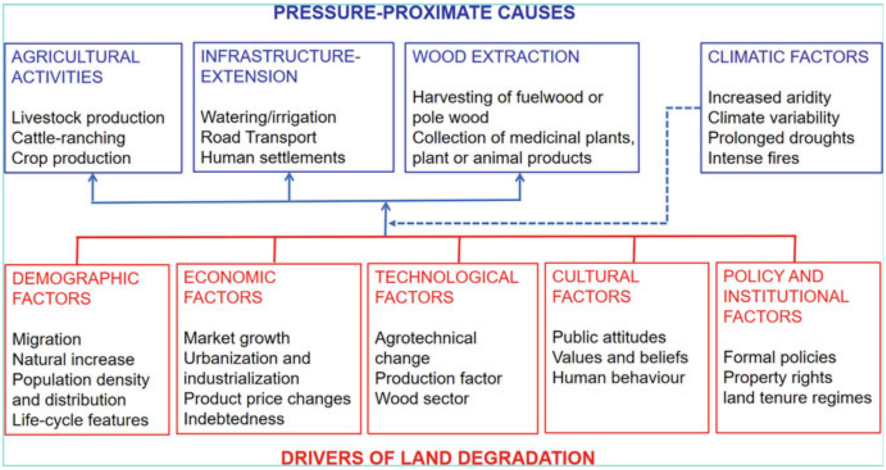

Fig. 5.1 Proximate and underlying driving forces of land degradation (based on Geist and Lambin 2004; IUCN 2015)

category include population pressure, poverty, lack of markets and infrastructure, poor governance, weak institutional frameworks and inadequate education (Nachtergaele et al. 2011). The various technological factors relate to agrotechnical change and production factors, and wood sector. Climate and climate variability are often intrinsic factors, climate change being considered either as a process or a driver of land degradation, or sometimes both (Olson et al. 2019). The expansion of agriculture and grazing lands into native vegetation, unsustainable agricultural and forestry practices, global consumption patterns and climate change are considered the main drivers of land degradation (Sutton et al. 2016; UNCCD 2017b).

According to IPBES (2018), the underlying drivers of land degradation include the high-consumption lifestyles in most developed economies, combined with rising consumption in developing and emerging economies; unsustainable levels of agricultural expansion, natural resource and mineral extraction, and urbanization; the growing demand for food, fodder, fuel and raw materials, which is increasing pressures on land and the competition for natural resources.

The main approaches to assess degraded lands at the global scale include expert opinion, satellite observations, biophysical models and taking inventories of abandoned agricultural lands (Gibbs and Salmon 2015). The Global Assessment of Human-induced Soil Degradation (GLASOD), which is based on expert opinion, provided information on the global distribution, intensity and the causes of erosional, chemical and physical degradation (Bridges and Oldeman 1999). Land degradation in Africa based on GLASOD global survey indicated that water erosion and wind erosion are the most widespread types of land degradation (46% and 38%, respectively), followed by chemical and physical deterioration of soils including, acidification, compaction and salinization and decline in soil fertility (16%). About 40% of lands on the African continent (65% of arable land, 30% of grazing land and

20% of forests) are under serious degradation due to soil erosion, soil nutrient depletion, soil organic matter decline as well as soil biodiversity loss (FAO and ITPS 2015). At the landscape scale, the degradation leads to a loss of biodiversity and causes negative microclimatic changes leading to desertification which affects around 45% of Africa's land area (FAO and ITPS 2015; Kirui and Mirzabaev 2014).

In Asia, about 59% and 30% of lands are degraded because of water erosion and wind erosion, respectively; 11% of lands are being affected by soil nutrient depletion, salinization, acidification, pollution and compaction (Bridges and Oldeman 1999). Water erosion occurs in regions with dry and wet seasons, covering South Asia to East Asia, particularly in the hilly and mountainous landscapes. Wind erosion occurs mainly in arid and semi-arid regions of Afghanistan, Pakistan, India and China. Acidic soils are widely distributed in tropical and subtropical regions of Southeast Asia, while salt-affected soils are widely distributed in the semi-arid and arid zones of central and West Asia.

Remotely sensed satellite imagery and GIS data have been utilized to identify the magnitude and processes of land degradation at global, regional and national levels (Gibbs and Salmon 2015). The FAO's Global Assessment of Land Degradation and Improvement project (GLADA) has quantified land degradation by using the normalized difference vegetation index (NDVI); the global extent of land degradation was estimated to be 2740 million ha, being 660 million ha in Africa and 912 million ha in Asia (Bai et al. 2008). By combining remote sensing based on NDVI measures with ground-level assessments, Kirui et al. (2021) reported land degradation occurred on about 51%, 41%, 23% and 22% of the total areas in Tanzania, Malawi, Ethiopia and Kenya, respectively, between the 1982 and 2016 periods.

The majority of the world's soil resources are in only fair, poor or very poor conditions, and soil erosion is a major threat to soil (FAO and ITPS 2015). Land degradation is still occurring at a rapid pace, with some 12 million ha of land degraded globally each year. Other causes of land degradation include rapid expansion and unsustainable management of croplands and grazing lands, deforestation and forest degradation, desertification, livestock overgrazing, declines in soil productivity with fertility losses linked to erosion, soil depletion and pollution, and soil salinization impacting about 7% of land area in more than 100 countries of the world.

There are five key ecosystem functions, i.e. food production, fibre provision, microclimate regulation, water retention and carbon storage that are being affected by land degradation. Short-term impacts of land degradation are on loss of biodiversity and reduction in water availability. In the long term, climate change and the occurrence of extreme weather events are reported to increase (Olson et al. 2019). Soils contain about 1500 Gt of organic carbon (Scharlemann et al. 2014), which is about 1.8 times more carbon than in the atmosphere and 2.3–3.3 times more than found in the terrestrial vegetation of the world (Ciais et al. 2013). Hence, land degradation, including land conversion of natural ecosystems, leads to soil carbon losses that impact the atmospheric concentration of CO_2 substantially. Roughly one-quarter of all anthropogenic greenhouse gas emissions come from the agriculture, forest and other land use sector (IPCC (Intergovernmental Panel on Climate

Change) 2014). Several meta-studies indicate that the magnitude of carbon loss could range from 20% to 59% (Poeplau et al. 2017; Wei et al. 2015; Murty et al. 2002). From a climate change perspective, land degradation plays an important role in the dynamics of nitrous oxide (N_2O) and methane (CH_4) emissions from the soil. N_2O is produced by microbial activity in the soil which is regulated by agricultural practices and climatic conditions, while CH_4 dynamics are primarily determined by the amount of soil carbon and water logging of soils.

5.2.2 Ecosystem Restoration

5.2.2.1 A Global Agenda for Ecosystem Restoration

In different regions of the world, restoration efforts are underway in forest, grassland, freshwater ecosystems and wetlands for restoring biodiversity, ecosystem services and mitigating the risk of global change, including exotic species invasions (Hobbs and Cramer 2008). In all these early efforts of restoration, the various restoration projects ranged in size from local to regional scales using site specific abiotic and biotic interventions. In just a few decades, however, the potential for restoration to repair degraded ecosystems led to a global movement. Restoration initiatives have now grown from small local projects to programmes aimed at restoring millions of hectares to recover biodiversity, ecological integrity and human well-being.

The period between 2021 and 2030 has been identified as the UN Decade on Ecosystem Restoration. The UN Decade on Ecosystem Restoration (2021–2030) aims to halt the degradation of ecosystems and restore them to achieve global goals to enhance peoples' livelihoods, counteract climate change and stop the collapse of biodiversity. This large-scale restoration of ecosystems can play a key role in limiting both climate change and species extinction. The United Nations Decade on Ecosystem Restoration aims to upscale forest restoration across hundreds of millions of hectares, healing degraded lands. It also provides an opportunity for many to benefit from the green jobs and income-generating possibilities that restoration presents, helping with economic recovery from the COVID-19 pandemic. The UN Decade on Ecosystem Restoration offers a vital opportunity to advance scaled-up, integrated approaches that reverse ecosystem degradation, biodiversity loss, and climate disruption and deterioration (Farrell et al. 2021).

The UN Decade on Ecosystem Restoration is an umbrella initiative, under which many other global restoration initiatives can be aligned and coordinated (Gann et al. 2019). The major international conventions (e.g. CBD, UNFCCC, Ramsar), intergovernmental programmes (e.g. IUCN, UNEP, UNCCD), international platforms (e.g. IPBES) as well as the 2015 UN Sustainable Development Goals (SDGs) have recognized large-scale restoration as a global priority for biodiversity conservation, combating desertification and land degradation and limiting the impacts of anthropogenic climate change. In addition to ambitious global initiatives, there are numerous regional initiatives, like the Great Green Wall, an African-led movement across the entire width of Africa (Box 5.1) and ecosystem-specific initiatives like the Global Mangrove Alliance, which intends to increase the surface of mangroves by 20% by 2030 (Valderrábano et al. 2021).

Box 5.1 African Forest Landscape Restoration Initiative (AFR100)
In 2015, the African Forest Landscape Restoration Initiative (AFR100) was launched to restore 100 million hectares by 2030. AFR100 contributes to the Bonn Challenge, the African Union Agenda 2063, the Sustainable Development Goals, and other targets. Presently, this initiative covers 31 African governments, and commitments have reached 130 million ha in June, 2021 exceeding the target of 100 million ha. This represents by far the most significant commitment under the Bonn Challenge, with the Africa region making up over 60% of the total share of the area committed under the Bonn Challenge. The initiative focuses on implementing forest landscape restoration action plans and monitoring systems, and raising private investment for restoration. The Secretariat of the AFR100 is held by the African Union Development Agency-NEPAD with support notably from the German Federal Ministry for Economic Cooperation and Development (BMZ), FAO, IUCN, the World Bank and the World Resources Institute (WRI).

Source: Mansourian and Berrahmouni (2021)

As mentioned in Strassburg et al. (2020), 137 countries have included restoration in their plans, 196 countries agreed to the Convention on Biological Diversity and Aichi Biodiversity Target 15 on ecological restoration under the Paris Climate Accord. To date, total commitments to the Bonn Challenge exceed 210.12 million hectares. FLR initiatives involve different activities, such as new tree plantings, assisted natural regeneration, agroforestry or improved land management to accommodate a mosaic of land uses, including agriculture, protected wildlife reserves, managed plantations, riverside plantings, etc. Moreover, the Bonn Challenge calls for the restoration of 350 million hectares of degraded and deforested landscapes by 2030, while the Sustainable Development Goals go further, still aiming for land degradation neutrality by 2030.

5.2.2.2 Scope of Ecosystem Restoration

Ecosystem restoration is the ‘process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed’ (SER 2004) with respect to its health, integrity and sustainability. During restoration, the structure, productivity and species diversity of the original community is re-established. However, the degraded ecosystem exhibits a lower level of structure and function, compared with that of the original ecosystem. Ecosystem restoration includes a continuum of restorative activities from reducing societal impacts, such as contaminants, to repairing

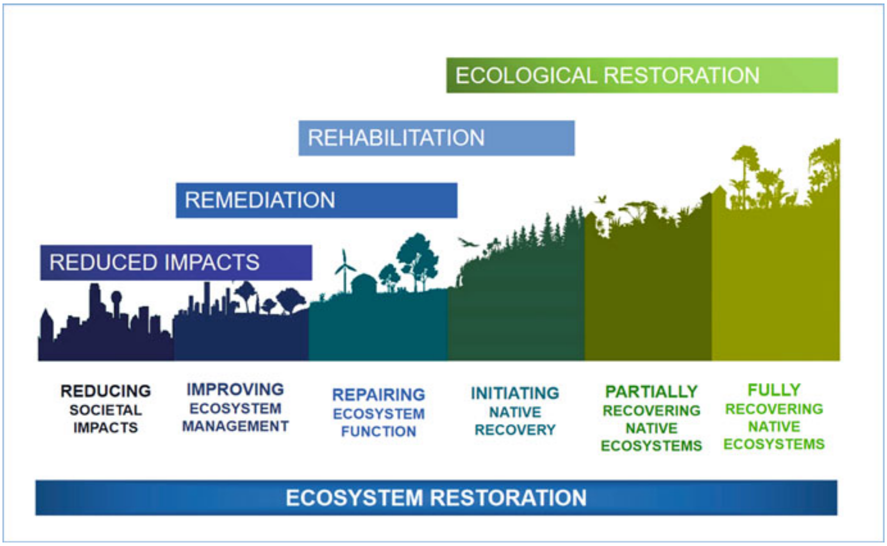

Fig. 5.2 The restorative continuum includes a range of activities and interventions for reversing ecosystem degradation and landscape fragmentation. Ecological health and biodiversity and ecosystem services increase from left to right on the continuum (adapted from Valderrábano et al. 2021, based on Gann et al. 2019)

ecosystem function in areas managed to produce goods and services, to full recovery through ecological restoration so as to remove degradation as well as assisting in recovering an ecosystem towards improved conditions for broad scale recovery (Gann et al. 2019) (Fig. 5.2). Ecosystem restoration**,** as defined by the UN Decade on Ecosystem Restoration, is much broader and refers to a wide range of management actions, from reducing societal impacts on ecosystems to partially or fully recovering native ecosystems through ecological restoration (United Nations Environment Programme (UNEP) 2021). Ecosystem restoration can be used to improve the integrity of degraded areas, which can lead to an overall increase in ecosystem area.

Ecosystem restoration plays an important role to conserve biodiversity and providing ecosystem services. A systematic meta-analysis of 89 restoration assessments has shown that restoration actions in a wide range of ecosystem types are effective in improving ecosystem services, particularly in the tropical regions (Rey Benayas et al. 2009). Thus, rehabilitation of degraded ecosystems combined can lead to high biodiversity conservation, livelihood benefits and long-term carbon sequestration. Restoring 350 Mha of degraded forest and agricultural landscape by 2030 under the Bonn Challenge could generate between US$0.7 and US$9 trillion in net benefits (Verdone and Seidl 2017). According to an estimate of the United Nations Environment Programme, investing US$1 in ecosystem restoration could generate US$9 in the form of different ecosystem services (Singh et al. 2021).

Strassburg et al. (2020) showed that restoring 15% of converted land in priority areas could avoid 60% of expected extinctions while sequestering 299 GtCO_2, or 30% of the total CO_2 increase in the atmosphere since the industrial revolution. This analysis also highlights the value of considering several ecosystems simultaneously in the spatial planning process, as these ecosystems vary in their relative contribution to the benefits (biodiversity conservation and climate change mitigation) and costs (implementation and opportunity costs). Ecosystem restoration has significant potential to contribute to nature-based solutions for societal challenges, including mitigation and adaptation to climate change (Valderrábano et al. 2021).

Box 5.2 Restoration Challenges for Degraded landscapes

The landscape restoration basically requires rich information on types of land, watershed, resources, finance, planning and policy on proper implementation, inclusive participatory and equitable development plan; watershed-based approach is required; knowledge of proper agroforestry-based interventions such as farmer-managed natural regeneration (near forest lands); proper choice of multi-purpose trees preferably local fertilizer trees for boundary plantations, hedge rows, wind breaks and silvopastoral systems; fruit-based agroforestry systems; mixed species plantations; scientific development of home gardens; fast-growing trees in waterlogged areas and to control seepage along canals; river-bank plantations; bamboo plantations; proper choice of species, density and management of shade trees in case of commercial plantations such as coffee, cocoa and spices cultivation; use of proper techniques and plant species for different problem soils; availability of knowhow and proper and sufficient germplasm; adoption of proper skill-development programmes for different stakeholders; and clear and adoptable policies and their implementations.

Based on Dagar et al. (2020a, b)

In many degraded landscapes, the land use challenges include change from natural forests to monoculture plantations (mixed species approach is more appropriate); low productivity of land; soil erosion; over extraction of fuelwood and non-timber forest produces (NTFP) in case of forest land; inadequate fodder supply presses over grazing; insecure land tenure (in case of forest land and landless farmers); lack of documentation of traditional knowledge; poor market linkages; lack of coordination among different stakeholders; and policy initiatives. On the basis of extensive information on ecological restoration through different agroforestry interventions in degraded landscapes (Dagar et al. 2020a, b), some restoration challenges are highlighted (Box 5.2).

5.2.2.3 Agroforestry, Forest and Landscape Restoration

Ecosystem restoration has been considered among the most effective strategies to mitigate climate change (Bastin et al. 2019). Furthermore, there is a large potential to regrow trees in croplands and urban areas, highlighting the scope for agroforestry in mitigating climate change. There are three scales at which agroforestry is relevant: plot-level, multifunctional landscapes and the interface of agricultural and forestry policies (van Noordwijk et al. 2019a).

Landscape scale restoration is being implemented in different regions of the world to reverse the damage done to biodiversity and human well-being by anthropogenic degradation of ecosystems (Rey Benayas and Bullock 2012; Hanson et al. 2015; Jones et al. 2018). The forest and landscape restoration (FLR) is a holistic approach aiming to balance diverse types of tree cover to achieve multiple benefits, based on the local socio-ecological conditions and stakeholder engagement (Mansourian and Parrotta 2018). FLR is a mechanism to achieve multiple goals, including climate mitigation, biodiversity conservation, socioeconomic benefits, food security and ecosystem services (IUCN and WRI 2014; Hanson et al. 2015; Chazdon and Brancalion 2019). FLR initiatives involve different activities, such as new tree plantings, assisted natural regeneration, agroforestry or improved land management to accommodate a mosaic of land uses, including agriculture, protected wildlife reserves, managed plantations, riverside plantings and more.

Agroforestry–Forest–Landscape restoration encompasses all activities that combine trees with an agricultural landscape comprised of crops or livestock (Hanson et al. 2015). It can result in a variety of land uses, ranging from vast tracts of dense natural forests, to high-yielding agroforestry systems and a mosaic of wooded areas in productive agricultural fields (IUCN and WRI 2014; Hanson et al. 2015). In addition, agroforestry can provide viable forest restoration pathways for highly degraded soils in all the ecologies with very low soil fertility or that are prone to erosion.

Throughout the Sahel, farmers have maintained a traditional land-use system within parklands. This is characterized by the deliberate retention of trees on cultivated land (Garrity et al. 2010). Farmers maintain 10–50 trees per farm hectare by identifying seedlings of useful species and allowing them to regenerate naturally in their fields. This practice is known as farmer-managed natural regeneration (FMNR). Trees are an integral part of their agricultural system. They provide food, fuel, fodder, medicines, wood for buildings and cash commodities, and contribute to soil fertility, water conservation and environmental protection. Over time, tree cover in Niger has increased. About 4.8 million hectares of *Faidherbia*-dominated farmlands were generated through FMNR. These landscapes now support up to 160 *Faidherbia albida* trees per hectare. Agroforestry, through the integration of trees on farms and in landscapes, has provided both products and services to achieve an improvement in livelihoods, the sustainable management of land and forests, and climate change mitigation and adaptation in degraded drylands in Niger (Reij et al. 2009).

Numerous reports of restoration successes provide evidence that the role of local and meso-level institutions is critical. According to Nzyoka et al. (2021) and Wainaina et al. (2021), stakeholders' participation in decision-making and inclusiveness in all the activities within the restoration agenda were vital in the restoration of the Shinyanga region in Tanzania. In a recent review of progress on restoration in Africa, Mansourian and Berrahmouni (2021) highlight local ownership as a critical factor of success and emphasize that the main challenges for restoration in Africa are largely institutional, social and economic as a whole. The Great Green Wall for the Sahara and the Sahel Initiative, led by the African Union, is one example of large-scale restoration (https://www.unccd.int/actions/great-green-wall-initiative) (Box 5.3; for details see Chapter 6 in this book).

Box 5.3 The Great Green Wall for the Sahara and the Sahel Initiative
This aims to restore 100 million hectares across Africa's drylands with local tree species and vegetation, greening landscapes, while sequestering 250 million tons of carbon and creating 10 million green jobs for the people by the year 2030. The Great Green Wall is the first flagship of the UN Decade on Ecosystem Restoration 2021–2030, and the United Nations Environment Programme (UNEP), through the Global Environment Facility and other donors, operates many restoration projects along with it (https://www.unep.org/news-and-stories/story/good-news-africas-great-green-wall). This will provide greater resilience to climate change in a region where temperatures are rising faster than anywhere else on Earth.

Asia is home to more than half of the world's population, and the pressure is on forests to provide income, food and water (IUCN 2017). Countries in Asia are taking keen interest to the restoration of their degraded and deforested lands to generate important benefits, with a focus on poverty alleviation, climate-smart agriculture and reversing deforestation (IUCN 2017). FLR initiatives involve different activities, such as new tree plantings, assisted natural regeneration, agroforestry or improved land management to accommodate a mosaic of land uses, including agriculture, protected wildlife reserves, managed plantations, riverside plantings and more. By integrating FLR into on-going environment and development programmes, countries can maximize the impact of their investment. Agroforestry is also a part of various restoration-focused initiatives, such as Reducing Emissions from Deforestation and Forest Degradation Plus (REDD+), the Bonn Challenge, United Nations' conventions to Combat Desertification through Land Degradation Neutrality and on Biological Diversity (Lin et al. 2021).

5.3 Emerging Challenges of Climate Variability

Warming trends and increasing temperature extremes have been observed across most of the Asian region over the past century (Hijioka et al. 2014). The Fifth Assessment Report of the IPCC has indicated that the numbers of warm days have increased and numbers of cold days have decreased, and the warming trend is expected to continue into the new millennium. Precipitation trends including extremes are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia (Hijioka et al. 2014). Terrestrial systems in many parts of Asia have responded to recent climate change with shifts in the phenology, growth rates and the distributions of plant species, and with permafrost degradation and the projected changes in climate during the twenty-first century will increase these impacts (Hijioka et al. 2014). Most of Southeast Asian countries are vulnerable to the effects of climate change, and countries like Myanmar, Philippines, Vietnam and Thailand are most at risk of extreme weather events (Eckstein et al. 2019). The growing prevalence and magnitude of environmental disasters and hazards make agroforestry critical for reducing climate change risks and costs (Lin et al. 2021). About 34% of global anthropogenic emissions of CO_2, CH_4, N_2O and fluorinated greenhouse gases are produced from the agricultural systems (Crippa et al. 2021). Contributions of sustainable agriculture, such as agroforestry, are critical in Southeast Asia where land use was responsible for 74% of GHG emissions from the food system in 2015 (Crippa et al. 2021).

According to Thompson et al. (2010) and Zewdie (2014), average temperature of the African continent is projected to increase by 3–4 °C in future. The changes in precipitation on the African continent at the end of the twenty-first century are expected to change across the different regions (Niang et al. 2014). The West African region is expected to experience a slight or no change in heavy precipitation, while precipitation in the Eastern and Central African region is projected to increase (Niang et al. 2014; Girvetz et al. 2019). For the Southern and Northern African regions, there is a projected decrease in total precipitation with Southern Africa recording an increase in heavy precipitations (Niang et al. 2014).

Drought is a component of the natural variability in climate on the African continent, with quite high intensities at monthly, yearly, decadal or century timescales (Ofori et al. 2021). Studies have shown that climate change, aerosol emissions, land use practices and subsequent land–atmosphere interactions are some of the mechanisms responsible for the occurrence of droughts (Masih et al. 2014;

Bhaga et al. 2020). Moreover, El Niño–Southern Oscillation (ENSO) and sea surface temperatures are considered as key factors influencing drought across Sub-Saharan Africa (Masih et al. 2014; Ofori et al. 2021).

The Sub-Saharan region is considered to be most vulnerable to the changing climate (Ringler et al. 2010; Thompson et al. 2010) because of the acute levels of poverty and the limited facilities needed to mitigate and/or adapt to the changing climate. The people in Sub-Saharan Africa greatly depend on precipitation to meet their water, food and energy needs (Thompson et al. 2010). For example, the prevalence of rain-fed agriculture in most of the region makes its food systems highly sensitive to the changing patterns in precipitation (Thompson et al. 2010).

5.3.1 Sea-Level Changes

Sea-level changes have been measured directly by tide gauge records, and since the 1990s by satellite laser altimetry. According to these observations, ocean temperatures are increasing, leading to ocean expansion, as ice sheets and glaciers melt, they add more water. The global-mean sea level (GMSL) has been rising unsteadily by about 1.56 mm year^{-1} since 1900, but the underlying causes of this trend and the multi-decadal variations are still poorly understood (Frederikse et al. 2020) (Table 5.1). The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of CMIP, ice sheet and glacier models. For these assessments, the uncertainty estimates represent the 90% confidence interval.

The rate of GMSL rise from 1993 to present has been measured at 3.34 mm year^{-1} based on data from the satellite altimeter record (Beckley et al. 2017). The Intergovernmental Panel on Climate Change (IPCC) reports have been publishing sea-level rise projections with increasing levels of confidence; in its 2019 report, the IPCC projected 0.6–1.1 m of global sea-level rise by 2100 (or about 15 mm year^{-1}) if greenhouse gas emissions remain at high rates (RCP8.5). By 2300, seas could stand as much as 5 m higher under the worst-case scenario. If countries do cut their emissions significantly (RCP2.6), the IPCC expects 0.3–0.6 m of sea-level rise by 2100 (https://earthobservatory.nasa.gov/images/148494/anticipating-future-sea-levels).

The Representative Concentration Pathway (RCPs) is used to calculate future projections based on near-term emissions strategies and their expected outcomes in the future. In this method, the RCP values refer to the amount of radiative forcing (in W m^{-2}) in the year 2100.

The impacts of sea-level rise include increased frequency and severity of flooding in low-lying areas, erosion of beaches and damage to infrastructure and the environment, including wetlands and inter-tidal zones and mangroves, with significant impacts on biodiversity and ecosystem. Researchers have predicted that as much as four-fifths of wetlands worldwide could be lost by the end of the century if sea levels

Table 5.1 Global mean sea-level change in meters relative to 1900

Period	Estimate (mm year^{-1})	Uncertainty (±mm year^{-1})	Reference	Measurement/ forecast model
1993–2020	3.34	0.40	Beckley et al. (2017)	Satellite altimetry
1993–2018	3.35	0.47	Frederikse et al. (2020)	Tide gauges
1900–2018	1.56	0.30	Frederikse et al. (2020)	Tide gauges

continue to rise. The coastal wetlands are highly important in the face of rising sea levels, as they reduce the impact of typhoons and tsunamis, as well as increase resilience to the impacts of climate change. The recent IPCC report predicts particularly grave consequences for Southeast Asia, one of the planet's most vulnerable regions to climate change (IPCC 2021). This region will be impacted by rising sea levels, heat waves, drought and more intense and frequent bouts of rain; however, Southeast Asia is projected to be warm slightly less than the global average, sea levels are rising faster than elsewhere and shorelines are retreating in coastal areas where 450 million people live (IPCC 2021).

5.4 Agroforestry for Climate Resilience

Agroforestry refers to land-use systems where woody perennials are deliberately used on the same land management units as agricultural crops and/or livestock, in some form of spatial arrangement or temporal sequence (Nair 1993) or 'trees on farm' (Zomer et al. 2014, 2016). When using the 'trees on farm' definition, more than 43% of the total global agricultural land includes at least 10% tree cover, representing over one billion ha of land worldwide (Zomer et al. 2014, 2016). In Sub-Saharan Africa, the proportion of agroforestry has been estimated at 29% of the agricultural land, accommodating 70 million people (World Bank 2004). Agroforestry can be an important FLR approach with the potential to restore degraded land by re-establishing ecological processes, structures and ecosystem functions, and also providing economic returns and the maintenance of livelihoods, local knowledge and culture (ICRAF 2021). Agroforestry-based restoration projects across the tropics have been documented comprehensively in a number of studies (Rahman and Baral 2020; Samsudin et al. 2020; Maimunah et al. 2018; Siarudin et al. 2021).

Using appropriate management practices, agroforestry increases crop yields and improves the livelihood security of farmers living in poverty, while helping them adapt to climate change (Pretty and Bharucha 2014; Waldron et al. 2017; Agroforestry Network, Vi-skogen 2018). About 2.4 billion people around the world depend on fuelwood from trees to cook food, and agroforestry has potential to support large parts of the rural population with fuelwood.

5.4.1 Agroforestry Systems and Practices in Asia and Africa

In the South and Southeast Asian and African regions, a multitude of agroforestry systems have evolved on over long periods that reflect the accrued wisdom and adaptation strategies of millions of smallholder farmers to meet their basic needs of food, fuelwood, fodder and plant-derived medicines. Some agroforestry practices in the Central Asian region include managed woodland for non-timber forest products, silvopasture, wind breaks, fruit-based agroforestry, alley cropping, riparian buffers and intercropping fruit trees with crops in home gardens and across the farm landscape. Moreover, across Central Asian countries, agroforestry can be an option to rehabilitate degraded lands and create environmental and social resilience. Regeneration of degraded lands through agroforestry offers the added benefit of producing food for communities, and supporting rural economies and subsistence livelihoods (Chazdon 2008; Hillbrand et al. 2017). Agroforestry can add a high level of diversity on degraded lands for supporting numerous ecological and production services (Singh et al. 2016; Dagar et al. 2016a, b; Gupta et al. 2019) as well as providing resilience to climate change impacts (Schoeneberger et al. 2012). In Southeast Asia, the concept of agroforestry has evolved from the plot-level integration of trees, crops and livestock ('taungya' in Myanmar and 'tumpang sari' in Indonesia) into a wide range of agroforestry practices that are worthy of greater promotion, capacity development and research. There is a clear relationship between the ecological characteristics of a region and the nature of the agroforestry systems. The passage of the ASEAN Guidelines for Agroforestry Development (the 40th ASEAN Ministers on Agriculture and Forestry meeting, held in HaNoi, Vietnam on 11 October 2018) has brought significant attention to agroforestry in the region, and has provided a favourable environment for targeted actions for inducing changes at the landscape level, and adopting agroforestry practices (Catacutan et al. 2018).

The role of agroforestry systems in human well-being and its climate adaptation and mitigation potential for South Asia have been reviewed by Dhyani et al. (2021). Mostly, the studies on AFS in the Asia-Pacific region have been carried out in India, China, Indonesia and Australia, with a focus on silvopastoral systems. AFS include multifunctional landscapes such as home gardens that secure food and support conservation of lesser-known underutilized biodiversity in Sri Lanka, Maldives, Bangladesh and India (Dhyani and Kadaverugu 2020). These tree-based land management practices and integrated agri-silvi-horti production systems that favour resource conservation and support conservation of traditional agrobiodiversity also ensures climate adaptation and mitigation in the region (Kumar et al. 2012).

Some of the common agroforestry practices in different regions of Africa include shifting cultivation, Taungya and Shamba systems, rotational woodlot systems, improved tree fallows, home gardens, parkland systems and silvopastoral systems (see Dagar et al. 2020a, b). Typically, agroforestry practices are multifunctional, although the type and magnitude of the goods and services produced by such practices vary greatly depending on the components involved and their management in the landscape (Kuyah et al. 2020). In parklands, a wide range of tree species are often grown at random spacing in cropped fields, which constitute the largest single agricultural land use in Sub-Saharan Africa. Some parklands are mono-specific (e.g. *Fadherbia albida* and *Borassus aethiopum*-based), but others have dominant tree species mixed with a range of tree and shrub species (Bayala et al. 2014). For some instances, the original species such as *Prosopis africana*, *Vitellaria paradoxa*, *Fadherbia albida* and *Parkia biglobosa* are retained, while cash plantations such as oil palm (*Elaeis guineensis*) are introduced along with others (e.g. *Adansonia digitata*).

In northern Ethiopia, the farmers were practising 61.2% of parkland AF followed by 19.4% rotational woodlots, 12.2% home garden and 7.1% boundary plantings as main AF practices, while the parkland dominated the lowland AF systems, but was uncommon in the highland part and 89% of woodlots AF practice were found in the highland agroecology (Manaye et al. 2021). There were 59 woody species in these AFS, where parkland had highest number of species (47) followed by home gardens (23), boundary plantation (11) and woodlots with 8 species. Thus, the strategic use of home gardens and boundary planting can improve tree diversity and carbon storage in Ethiopian dryland ecosystems.

5.4.2 AFS of Stress Ecologies

AFS sustain the agricultural productivity in stress environment (salinity, alkalinity, waterlogging, acidity and desertification due to erosion). Extreme condition of water erosion is formation of gullies and ravines, which can be rehabilitated through suitable agroforestry systems not only for ecological services but also for livelihood security (for more details, see Dagar and Singh 2018). Agroforestry systems, particularly in degraded landscapes, have enormous benefits not only in the provision of food for local people, but also provide multiple environmental services and influence the socio-cultural values. Agroforestry technologies can be applied to rehabilitate or restore degraded lands from agriculture, soil erosion, deforestation, rangeland degradation, salinity mining sites and over-extraction at various scales, from plot to farm level to large agricultural and farming enterprises (see Dagar and Gupta 2017; Dagar et al. 2020a, b).

Salinity afflicted landscapes, which now occupy nearly a billion hectares (about 10% of land area) in world, have their origin either due to natural or man-induced causes. The use of agroforestry systems is now being put forward as a viable alternative to rehabilitate salt-affected and waterlogged soils (Dagar et al. 2019). Trees are considered to be more tolerant to these stresses than the annual species and arable crops. In order to rehabilitate salt-affected lands, appropriate tree-planting techniques and choices of tree species are very crucial for reducing mortality and consequently for improvement in the initial establishment of saplings. In alkali soils, a hard *kankar* layer of calcium carbonate is generally found at a depth of about 1.25–1.5 m which acts as a barrier for root penetration. A pit-auger-hole technique of tree plantation has been developed and perfected (Singh et al. 1998; Dagar et al.

2001; Singh and Dagar 2005). Tolerant tree species overcome high concentrations of sodicity by different regulatory mechanisms. There are very few wild plant species, which are able to grow on highly sodic soils (pH > 10). On the basis of experiments conducted on highly alkali soils, *Prosopis juliflora*, *P. alba*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata*, *Eucalyptus tereticornis*, *Terminalia arjuna*, *Pongamia pinnata* and *Parkinsonia aculeata* demonstrated a higher tolerance. These trees along with grasses such as *Leptochloa fusca*, *Brachiaria mutica*, *Panicum laevifolium*, *P. antidotale*, *P. purpureum*, *Setaria anceps* and *Chloris gayana* form ideal silvopastoral systems on highly alkali soil, which not only give fuelwood and fodder but also ameliorate the soil to the extent that after 4–5 years of afforestation; arable crops can be cultivated on these reclaimed soils. Among fruit trees, *Carissa carandas*, *Punica granatum*, *Achras zapota*, *Aegle marmelos*, *Emblica officinalis*, *Psidium guajava*, *Syzygium cuminii* and *Ziziphus mauritiana* are successful on alkali soil with pH up to 9.8.

Acid soils occupy approximately 30% of the world's total land area and it has been estimated that over 50% of the world's potential arable lands are acidic (Zhang 2010) and increased solubility and toxicity of Al, Mn and Fe; deficiency of Ca and Mg; reduced availability of P and Mo and reduced microbial activity with decreasing pH are the characteristic features and constraints for crop production in these soils. In north-eastern Himalaya regions of India, Alder (*Alnus nepalensis*)-based agroforestry systems involving arable and high value crops like cardamom (*Elettaria cardamomum*), large cardamom (*Amomum subulatum*), pineapple (*Ananas sativum*), many fruit trees, tuber crops like turmeric, ginger, colocacia and taros make successful and sustainable agroforestry systems, which besides providing good economic yields also ameliorate soil by fixing nitrogen and organic matter.

In humid tropics, the soils are generally acidic and low in nutrient availability. Some carry toxic levels of iron and aluminium. The home gardens, coffee and cacao production systems, plantation-based multi-tiered dense cropping systems and alley cropping on sloping lands represent typical agroforestry systems on acid soils (Kumar and Nair 2004; Dagar et al. 2014a, b, 2016b, 2020a)

5.4.3 Climate Resilience and Agroforestry

Climate resilience is the ability to anticipate, prepare for, and respond to hazardous events, trends or disturbances related to climate. While improving climate resilience involves taking steps to better cope with these risks. As reviewed by Mbow et al. (2014a, b) and Dagar et al. (2020a, b), the agroforestry systems involve a number of land management practices like crop diversification, long rotation systems for soil conservation, home gardens, boundary plantings, perennial crops, hedgerow intercropping, live fences, improved fallows or mixed strata agroforestry. Thus, agroforestry, now, is considered promising land management system that provides multiple benefits, including increased farm productivity, water quality improvement, mitigation of climate change, soil erosion control as well as increased soil fertility and environmental services (Jose et al. 2012; Dagar and Tewari 2017; Agroforestry Network, Vi-skogen 2018).

5.4.3.1 Increasing Crop Yields

In Niger, farmers have restored more than five million ha of semi-desert landscape into an open woodland agroforestry system by planting more than 200 million trees, including the native *Faidherbia albida* which fixes nitrogen and increases soil organic matter. As a result, crop yields have increased, areas with a high density of on-farm trees have produced a grain surplus, even, during drought years (Yamba et al. 2005), household incomes have nearly doubled and, in some area, biodiversity improved substantially (WRI 2008).

Based on a total of 1106 observations from 126 peer-reviewed publications dealing with major AFS (alley cropping, hedgerows, dispersed intercropping, multi-strata agroforests, parklands, windbreaks, boundary planting and planted improved fallows), Kuyah et al. (2019) inferred that across ecological conditions, agroforestry significantly increased crop yield, total soil nitrogen, soil organic carbon and available phosphorus compared to the control. Agroforestry practices also reduced runoff and soil loss and improved infiltration rates and soil moisture content. They further concluded that no significant differences were detected between the different ecological conditions, management regimes and types of woody perennials for any of the ecosystem services. Probably this is the first meta-analysis that shows that agroforestry systems in Sub-Saharan Africa increase crop yield while maintaining delivery of regulating/maintenance ecosystem services without sacrificing crop productivity.

5.4.3.2 Resilience Through Improved Microclimate

In drylands, trees and shrubs are often mixed with annual crops and in the rangelands modify microclimatic factors such as wind speed, air and tissue temperatures, relative humidity and radiation, saturation deficit of under-storey crops and consequently affecting evaporation (Brenner 1996; Soni et al. 2017). Therefore, compared to an open environment, the modified microclimate under trees has reduced solar radiation, lower temperature regime, higher humidity, lower rates of evapo-transpiration and higher soil moisture levels, affecting both crop growth and livestock performance.

Shade trees in coffee systems affect the maximum and minimum daily temperature, and can decrease the mean daily temperature by up to 4 °C (Beer et al. 1998). More specifically, shade levels of 50% can decrease the mean daily temperature by 2−3 °C (Rahn et al. 2018), decrease the maximum air temperature by 3 °C and increase the minimum temperature by 1 °C without compromising coffee yield (Moreira et al. 2018). In Niger, *Fadherbia albida* shade-induced reduction of soil temperatures (at 2-cm depth) was observed 5–10 °C lower depending on the movement of shade, particularly at the time of crop establishment, contributing to the better growth of crops under these trees (Vandenbeldt and Williams 1992).

Trees can also lower mechanical impact of wind/rain speeds to minimize damage on newly established crops. In coffee and cacao plantations, shade trees have been observed to buffer high and low temperature extremes by as much as 5 °C (Beer et al. 1998). Further, Jonsson et al. (1999) also observed weekly low mean soil temperature at 5-cm depth, at Saponé, Burkina Faso under large and small trees of néré (*Parkia biglobosa*) and small trees of karité (*Vitellaria paradoxa*), showing that the combined beneficial effects of temperature modifications and soil fertility could exceed the negative effect of tree shade. Niether et al. (2018) mentioned that shade tree pruning manages microclimatic conditions in favour of cocoa (*Theobroma cacao*) production while tree diversity is maintained. Cocoa agroforestry systems are temporal dynamic systems, and pruning timing and intensity of shade trees is pivotal for balancing light and water availability under seasonally varying environmental conditions to conserve microenvironments for cocoa production with less exposure to unfavourable climate.

Moderation of pasture microclimate provided by trees further protects livestock from heat stress, wind, chills and severe weather events. Consequently, the use of agroforestry systems is an economically feasible way to protect crop plants from extremes in microclimate and soil moisture. Trees with a dense canopy and intense litter fall can reduce evaporation from the soil surface by modifying microclimate.

Recently, Gomes et al. (2020) stated that the climate models indicated that the annual mean air temperature is expected to increase 1.7 °C ± 0.3 in Brazil, which will lead to almost 60% reduction in the area suitable for coffee production in unshaded plantations by 2050. However, the adoption of agroforestry systems with 50% shade cover can reduce the mean temperatures and maintain 75% of the area suitable for coffee production in 2050, especially between 600 and 800 m altitude. Further, major shifts in areas suitable for coffee production may take place within three decades, potentially leading to land conflicts for coffee production and nature conservation. Incentives that contribute to the development of coffee agroforestry systems at appropriate locations may be essential to safeguard coffee production in the southeast of Brazil and the same is true for producers of coffee, which is an important cash crop for approximately 25 million smallholder farmers and 100 million livelihoods in many countries in Africa, Mesoamerica and South America (Pendergrast 2010). Coffee-based agroforestry systems consist of coffee plants intercropped with shade trees, which can increase nutrient cycling, biodiversity, carbon storage, and provide a moderate microclimate (Duarte et al. 2013). The microclimate created by the trees results in lower mean air temperatures and higher soil moisture in coffee agroforestry systems.

5.4.3.3 Resilience Through Water Regulatory Services

In arid and semi-arid regions, crops commonly utilize less than half of the annual rainfall productively, with the remainder lost as runoff, evaporation or drainage. Use of groundwater by trees that is inaccessible to shallow-rooted crops can be verified by comparing the relative concentrations (δ values) of the stable isotopes ^{2}H or ^{18}O in cell-sap and water from possible sources, as differences commonly exist in the natural isotopic composition of groundwater and soil water. Use of this technique to compare the sources of water exploited by trees and crops in agroforestry can indicate whether their water use is competitive or complementary (Smith 2008). To understand the extent of competition for water in windbreak systems, sources of water used by windbreak trees and crops were investigated at two sites in Niger; at both sites, pearl millet (*Pennisetum glaucum*) was sheltered by neem (*Azadirachta indica*) windbreaks, but the depth of groundwater at the two locations was markedly different. In the Majjia Valley, in central Niger, the water table occurred at a depth of 6–10 m where the production of millet increased by 20–25% but at another site at Sadoré, where groundwater was at 35 m, the establishment of windbreaks not resulted in enhanced crop production (Smith 2008); therefore, such differences in the impact of windbreaks on crop productivity might had arisen because competition for water was less severe at locations where groundwater was accessible to tree roots. Tree species known to have low water use should be chosen and they should have root systems that do not spread laterally for long distances in the crop rooting zone; if warranted trenching can be used to prune lateral roots. Once established, demand for water by windbreak trees should be reduced by pruning of the canopy. The timing and severity of pruning and the desired shape of the canopy should be optimized by on-farm testing, but the goal of pruning windbreaks should be to minimize demand for water by the trees while maximizing control of wind erosion.

Compared to other plant forms, trees extract, transpire and evaporate much of the rainfall, and at the same time in combination with other vegetation, mainly grasses in silvopastoral systems dramatically reduce surface runoff and improve infiltration rate and hence contribute to increasing and maintaining the soil moisture and the belowground storage fraction. However, quantitatively and sometimes qualitatively, the effect of trees on the water cycle, and hence their contribution to the water regulation service is much stronger than that of non-tree plants (Safriel 2014). The primary mechanism through which trees improve water regulation is improved infiltration rather than soil moisture. Empirical studies attributed high infiltration rates in agroforestry to improved hydraulic conductivity of the soil and better porosity (Nyamadzawo et al. 2008). Water regulation was more strongly improved under agroforestry in semi-arid than in humid locations (Kuyah et al. 2019) and the effects were significantly greater on Lixisols (predominant in semi-arid areas) compared to Luvisols and Nitisols (in humid and sub-humid regions, more fertile and free draining soils).

Trees may also increase rainfall because their foliage is generally darker with lower albedo (reflection of solar irradiation) than drylands soils which are mostly pale with higher albedo. Surfaces with lower albedo absorb more solar energy, heat up more easily and drive convection of air, which triggers the formation of clouds and rainfall (Safriel 2014). Mean annual albedo varies in West Africa from 60% in the arid zone to around 15% in the humid coastal areas, a difference attributed to a concurrent increase in tree cover (Fuller and Ottke 2002) and increased rainfall in the

Sahel is attributed due to albedo changes (Samain et al. 2008). Agroforestry improved infiltration and soil moisture content compared to the control and the effect on infiltration was greater than that on soil moisture (Kuyah et al. 2019), and based on the studies conducted in Kenya, Nigeria and Zimbabwe, they reported that agroforestry performed best in terms of erosion reduction ecosystem services, 5 and 10 times better than controls for runoff and soil loss both in humid and semi-arid regions. Trees have been shown to reduce soil loss by forming barriers that slow runoff and capture sediments, protecting soil aggregates from direct raindrops and improving soil structure.

Trees may increase groundwater use efficiency by capturing and redistributing water which has percolated below the crop rooting zone, using soil moisture for conversion to tree biomass when crops or grasses are not actively growing and improving infiltration rates and soil water-holding capacity (Wilson and Ndufia 2014). The composition of deep-rooted perennial trees with shallow-rooted short-lived crops and grasses in AF mode provides opportunities for complementarity and facilitation but also risk of competition between trees and shallow-rooted species. Crop and grass roots are mostly in the top 20–70 cm soil horizon depending upon the soil type, where soil moisture is highly variable, due to evaporation and rainfall, particularly in dry ecologies. A mature tree has a combination of lateral roots in surface zones, extending well beyond the tree canopy edge, and overlapping with the crop rooting zone, and deep roots reaching several meters at times up to 20–30 m belowground (depending on the nature of soil) which may access groundwater. The overlap of tree and crop root systems leads to competition for moisture. Facilitation occurs when shallow-rooted species take up and benefit from water released by trees. For example, at night, many tree species, including *Vitellaria paradoxa* and *Parkia biglobosa* of the West African savannah, release moisture taken up from wetter soil layers into drier upper soil horizons, a process known as hydraulic redistribution (Bayala et al. 2008). In dry systems at the peak of the dry season, the released water may comprise 17–81% of tree transpiration the following day (Neumann and Cardon 2012). However, evidence of its significance for crop growth is limited as much of the redistributed water may be re-absorbed by the tree. In some cases, for instance, crops grown with *Prosopis cineraria* get benefit of its association and crop yield is higher than when grown alone.

5.4.3.4 Resilience Through Soil Erosion Control and Sand Dune Stabilization

Based on studies in Kenya, Nigeria and Zimbabwe, Kuyah et al. (2019) reported that agroforestry systems performed best in terms of erosion reduction, 5 and 10 times better than controls for runoff and soil loss both in humid and semi-arid conditions, and erosion control with agroforestry was more effective when either shrubs or trees were planted. Williamson et al. (1996) also showed that riparian buffer strips and hill slope forestation reduced sediment export by 85%. The trees reduce soil loss by forming barriers which help in slowing down the runoff, protecting soil aggregates from the direct impact of raindrops and improving soil structure by adding organic matter which in turn enhance infiltration rate Nyamadzawo et al. 2008; Kuyah et al. 2019).

Dryland trees and shrubs also protect soils from wind erosion. Scattered trees and shrubs reduce wind erosion by reducing the wind velocity, sheltering the soil from the erosive force of the wind by covering a proportion of the surface and trapping the sand particles. The most important measures for sand dune stabilization are covering the area under trees and providing a surface cover of grasses followed by their protection against biotic interference. Tewari et al. (2014) and Gupta and Dagar (2017) gave a detailed account of sand dune stabilization in Indian sub-continent.

The vegetation for sand dune stabilization is highly drought tolerant with deep root system capable of extracting moisture from lower soil depths. Trees such as *Acacia tortilis*, *A. jacquimontii*, *A. leucophloea*, *A. senegal*, *Salvadora oleoides*, *Capparis decidua*, *Ailanthus excelsa*, *Tecomella undulata*, *Hardwickia binata*, *Azadirachta indica*, *Balanites roxburghii*, *Prosopis cineraria*, *P. juliflora* and *Holoptelia integrifolia* in combination with grasses such as *Cenchrus ciliaris*, *C. setigerus*, *Dichanthium annulatum* and *Panicum antidotale* have been found most successful for sand dune stabilization. Silvopastoral system is most viable, sustainable and profitable system in dry ecologies.

5.4.3.5 Resilience Through Improved Soil Fertility/Nutrient Use Efficacy

Trees in agroforestry systems improve soil fertility through recycling of nutrients from the deep soil horizons to the topsoil layers and by fixating atmospheric nitrogen by fertilizer (leguminous) trees. Sileshi et al. (2011, 2014, 2020) emphasized on the integration of fertilizer trees in crop fields and their role in improving soil fertility, nutrient and water use efficiency and sustaining crop yield. Role of agroforestry systems in reclamation of degraded salt-affected and other problem soils including desertification and ravine lands has been well documented by many workers (Quadir et al. 2007; Qureshi et al. 2008, 2018; Dagar et al. 2014a, b; Liu et al. 2015; Dagar and Minhas 2016; Vargas et al. 2018). In all these conditions AFS ameliorate soil by adding organic matter both from aboveground (litter) and belowground (root decomposition).

The recycling of nutrients by trees takes place either through capture of nutrients from the deep soil horizons or interception of nutrient leaching beyond the crop rooting zone by tree roots (Kimaro et al. 2014). These nutrients are then released to the topsoil horizons through litter and root turnover. These processes are important in the recycling of nutrients in agroforestry systems for the ecological sustainability of AFS such as improved fallows, woodlots, hedgerow plantations and other practices common in dryland areas. The recycling of phosphorus (P) by trees is usually limited by high P-fixation in acid soils, low mobility in the soil and low foliar P concentration (Young 1997). Trees also accumulate other nutrients from the soil and may alleviate nutrient deficiencies, especially of potassium (K) that can arise when sufficient levels of N and P are supplied (Soni et al. 2017). Agroforestry transfers nitrogen from N-fixing trees to nearby crops. The transfer takes on the surface and belowground through decomposition of pruning or litter, root and nodule turnover, roots exudates via mycorrhizal connections and via the build-up of soil organic matter (Smithson and Giller 2002). The amount of N fixed varies widely among species (Sileshi et al. 2020) but for fast-growing tree species like *Sesbania sesba*n, *Cajanus cajan*, *Gliricidia sepium* and *Tephrosia vogelii*, fixation can accumulate about 100–200 kg of N per hectare per year. These amounts are substantial and can replenish soil N to levels sufficient to grow up to three subsequent maize crops on N-deficient sites (Mafongoya et al. 2007).

Trees also improve soil structure and fertility through the build-up of soil organic matter (SOM). Trees add SOM by fixing carbon during photosynthesis and subsequent transfer to the soil through litter fall and root turnover. These plant materials are then converted to SOM by soil microbes through decomposition and humification processes. Besides, nutrient supply, the decomposition of SOM may increase plant-available nutrients in the soil through the reduction of P-sorption capacity of soil and supplying energy sources to soil micro-organisms responsible for nutrient cycling (Barrios et al. 2012). It is natural to find higher populations of micro-organisms in soils under agroforestry compared to treeless land use. Besides improving soil quality, micro-organisms, such as mycorrhizal fungi, enable terrestrial plants to effectively access nutrients and water under stress conditions by forming association with plants that can alleviate the stress symptoms. Thus, trees drive nutrient cycling and transformation in an ecosystem through their influence on SOM, soil micro-organisms and chemical processes in the soil.

Faidherbia–maize system in Tanzania and the *Faidherbia–Eragrostis* system in Ethiopia are traditional agroforestry practices in which *Faidherbia albida* is retained and managed by farmers for soil fertility improvement and provision of other ecosystem services such as dry-season fodder for livestock. Other dryland agroforestry practices in Eastern Africa for soil fertility management include improved fallow and rotational woodlots in Tanzania and Kenya. Fallows of fertilizer trees can improve soil fertility at levels sufficient to reduce inputs of N and P fertilizers by 50% (Kimaro et al. 2009).

5.4.3.6 Some Success Case Studies

Case 1: Greening Drylands of Kenya with Agroforestry (Magaju et al. 2020; Niagi 2021)

In Kenya, about 80% of the terrain is dryland and only less than 20% of farmland is suitable for some kind of cultivation. The dried-out soils create a hard pan that does not allow to penetrate rain water and roots of crops. Due to inadequate rains and highly degraded soils, farmers are unable to get the required crop yield making the livelihood measurable. In an attempt to improve their lot 35 thousand poor farmers have joined the Dryland Improvement Program (DryDev) under a donor-led project that is turning arid Kenya into green farms which works in concert with the IFAD-EU funded Drylands Restoration Project to regreen their lands mainly with agroforestry, joining peers in Burkina Faso, Ethiopia, Mali and Niger. More than 7000 farmers in south-eastern Kenya have adopted dryland agroforestry. The project is funded by the Netherlands Ministry of Foreign Affairs and humanitarian group World Vision and DryDev has been training farmers in Africa to transition from subsistence farming and reliance on charity to agriculture (mainly agroforestry) that is productive and environmentally friendly. Some of the technologies being used to boost dryland agroforestry in Kenya include mulching, manure application, surface water harvesting, and the use of zai-pits, bowl-sized holes into which food crops are sown. In *zai-pit* technique the hard surface pan is broken, which has toughened up over time here due to desertification.

The farmers have started planting of multipurpose trees like neem (*Azadirachta indica*), *Melia volkensii*, *Senna alexandrina*, tamarind (*Tamarindus indica*), mango (*Mangifera indica*), orange (*Citrus* × *sinensis*), papaya (*Carica papaya*), custard apple (*Annona squamosa*), yellow passion fruit (*Passiflora edulis*), banana (*Musa* spp.), etc. and cultivation of cereals (maize, sorghum), pulses (green gram, cowpea, pigeon pea), vegetables (kale-cv of *Brassica oleracea*, pumpkin-*Cucurbita* spp., etc.) and forage crops such as alfalfa (*Medicago sativa*, also called lucerne), *Brachiaria* grass in agroforestry mode. Almost each farm keeps livestock. Studies by World Agroforestry on dryland agroforestry indicate that the agroforestry technologies are not only boosting food security for struggling farmers but also reducing environmental pollution, because farmers are cutting down on the use of chemicals and fertilizers (Niagi 2021). The honey production has also increased at farms because more bees are now visiting the trees and crops. The community facilitators are armed with ‘Regreening Africa’s app’, a data collection tool that makes it easy to map sites where dryland agroforestry is taking place. The app users record data and take photographs that help researchers innovate new ways to overcome the climate and topography barriers.

Case 2: Restoring Landscapes Through AF-Sidhi Experiences (WRI India 2020)

The Government of India has committed to a landscape approach to restoration under several international agreements and national targets. To achieve these targets, a first step is to identify the potential for restoration and estimate the environment and development benefits that could follow. The landscape approach brings together stakeholders who identify and implement practices to achieve an optimal balance of ecological, social and economic benefits from forests and agricultural landscapes in the form of agroforestry. World Resources Institute India (WRI India 2020) identified a remote, tribal dominated and highly vulnerable to climate change, Sidhi district of Madhya Pradesh in Central India as a representative of the land use challenges and socioeconomic and environmental issues confronting other underdeveloped landscapes in India and around the world. Landscape restoration can improve local livelihoods in districts with few other opportunities. Siddhi has an area of about 363,000 hectares with potential for restoration account for 75% of the total area of the district. Eight landscape restoration interventions as suitable for the district: assisted natural regeneration, mixed-species plantations, bamboo plantations, farmer-managed natural regeneration, riverbank plantation, trees on boundaries, agri-horti-forestry (a system called *wadi*) and pastureland development, were identified.

There are several successful examples of landscape restoration activities in Sidhi that can be scaled up. For instance, communities restored more than 2400 hectares of bamboo forests over four years in partnership with the forest department with a benefit sharing agreement. These bamboo forests continue being protected by the communities even though the project has ended and benefits have not been shared. Clarifying a benefit sharing mechanism and tenurial security aspects could enable scaling of these practices. It is estimated that restoration of Sidhi's forests through plantation or regeneration could sequester more than 7 million Mg of carbon over 10–20 years and increase forest carbon stock by 37% (FSI 2015), based on forest type and species planted.

Over the medium and long terms (5–7 years), value chain interventions could lead to development of microenterprises around six tree species: goose berry (*Emblica officinalis*), bamboo (*Bambusa/Dendrocalamus* spp.), jackfruit (*Artocarpus heterophyllus*), mahua (*Madhuca indica*), moringa (*Moringa oleifera*) and palash (*Butea monosperma*). Potential tree-based enterprises that could be set up in Sidhi include oil extraction, cattle feed production, and handicrafts. Pastureland development to increase the availability of fodder, forage and green manure is a key restoration intervention which would reduce soil erosion and improve soil nutrition and health (WRI India 2020).

Case 3: A Tale of an Enclosure: An Ethiopian Success Story (Getahun 2020)

In 2017, when 'World Vision Ethiopia', a non-governmental organization, started implementing the Reversing Land Degradation in Africa by Scaling-up Evergreen Agriculture (Regreening Africa) project in collaboration with World Agroforestry (ICRAF) in Ethiopia's Alage 'kebele' in Shashogo District of the Southern Nations and Nationalities and Peoples' Region, the farmers in the area gathered for a community meeting and agreed to enclose a stony, overgrazed and eroded piece of land that could not be used for crop production. Reluctantly, farmers enclosed a piece of barren land and stopped grazing and cutting of trees completely. They were surprised to see it soon filled with grasses, shrubs and trees (natural regeneration) that brought many benefits for the community. Out of enthusiasm, they planted 17 thousand trees of *Grevillea robusta* in addition to timber trees of *Acacia saligna*, *Azadirachta indica* and *Cordia africana*. Regreening Africa also provided avocado (*Persea americana*), mango and coffee trees to farmers and they have planted them on their own private land to provide fruit for nutritional benefit as well as income. 'Regreening Africa' is an ambitious 5-year project that seeks to reverse land degradation among 500,000 households, and across 1 million hectares in eight countries in Sub-Saharan Africa. By incorporating trees into croplands, communal lands and pastoral areas, regreening efforts make it possible to reclaim Africa's degraded landscapes. There are many such success stories.

5.5 Assessing Resilience to Climate Change

Functioning and integrity of terrestrial ecosystems in twenty-first century is highly threatened by the on-going changes in climatic conditions (Bellard et al. 2012). Under the influence of climate change, the ecological restoration is supposed to exert additional pressure on ecosystems which are already exposed to human induced disturbances, and this may reduce the success of long-term restoration projects (Palmer et al. 2008; Timpane-Padgham et al. 2017). The recent studies on climate change are utilizing trait-based vulnerability assessments for determining potential impacts and inherent natural sources of resilience to climate change for individual species (Williams et al. 2008; Foden et al. 2013; Hare et al. 2016). According to Walker et al. (2004), resilience is the capacity of an ecosystem to absorb disturbance and reorganize by retaining its essential functions, identities, structures and feedbacks. This concept of resilience gives the idea, whether the ecosystem services will be retained or lost. It has been suggested that the resilience approach to restoration can promote adaptation of the ecosystem to future climate changes through restoration of dynamic processes which foster natural variability and biological diversity within ecological systems, and reduce the chances of dramatic ecosystem change, drastic shift in population structure, or the loss of ecosystem services (Hansen et al. 2003; Folke et al. 2004; Walker and Salt 2012). Table 5.2 shows illustrative examples of potential indicators which could be applied for the assessment of resilience of ecosystem services to climate change.

Anjos and de Toledo (2018) suggested a strong correlation between the resilience and the structure of the ecosystem. Over a broad-scale climate gradient, the principle of maintaining the structure and function of an ecosystem at a stable state indicates that each stable state is strictly adapted to a specific set of abiotic conditions, enclosed in a multidimensional niche of climatic conditions (Hirota et al. 2011). This theory of ecological stability predicts that if a critical threshold of the resilience of an ecosystem is surpassed due to climatic changes, a catastrophic transition between the stable states of ecosystem can be anticipated (Scheffer and Carpenter 2003). Therefore, it is essential to investigate resilience of an ecosystem, since it plays a critical role in coordinating transitional events between the stable states of ecosystems (Gunderson 2000). Based on these ecological concepts, Anjos and de Toledo (2018) investigated the resilience of the three stable ecosystems viz., forest, savanna and grassland, in South America. Results of their study indicated that the most productive and most biodiverse ecosystem, i.e. forest was more vulnerable to changes in climatic conditions, as compared to savanna or grassland. According to this study, forests exhibited least resistance to climatic stress, and showed greater

Table 5.2 Illustrative examples of potential indicators of the resilience of ecosystem services to climate change. (Source: Epple and Dunning 2014)

Ecosystem	Subject of assessment	Ecosystem characteristics	Possible indicators
• Mountain grassland	• Resilience of erosion control service to intensive precipitation events	• Vegetation cover • Density of near-surface root system • Abiotic factors (soil type, slope)	• Signs of existing degradation (e.g. reduced vegetation cover or high livestock densities) • Structural and species diversity • Presence of key species with strong soil retention capacity • Abiotic factors determining general susceptibility to erosion (soil type, slope)
	• Resilience of erosion control service to more prolonged drought periods	• Vegetation cover • Density of near-surface root system • Abiotic factors (soil type, slope)	• Signs of existing degradation (e.g. reduced vegetation cover or high livestock densities) • Percentage of drought-sensitive species • Structural and species diversity • Presence of key species with strong soil retention capacity • Abiotic factors determining general susceptibility to erosion (soil type, slope)
• Forest	• Resilience of food provisioning service (game animals) to temperature rise	• Habitat quality for important game species • Existence of healthy populations of important game species	• Signs of current overhunting or other anthropogenic pressure • Location of the site in relation to range margins of currently occurring and potentially immigrating game species • Isolation of the site from potential source areas for immigration of game species • Location of the site in relation to range margins of dominant tree species and species providing food for important game species • Diversity of species providing food for important game species
• Coral reef	• Resilience of aesthetic / recreational service to high water temperatures	• Species diversity • Species abundance • Structural diversity	• Current temperature regime in relation to temperature tolerance levels • Current levels of species diversity • Level of eutrophication and other degrading factors

chances of losing resilience due to climate change, which could lead to transition of this ecosystem to low density ecosystems, i.e. savanna and grassland.

Timpane-Padgham et al. (2017) proposed that the identification of the sources of ecological resilience is the critical step determining ecosystem restoration in a changing climate. Grimm et al. (2013) reported that changes in climatic conditions results into biome shifts, which influences demography and growth of vegetation, leading to alteration in productivity of the habitat. Moreover, Sharma and Goyal (2017) investigated the impact of climatic perturbations on the status of ecosystem resilience and observed that the response of productivity to changes in climatic conditions is also influenced by vegetation types. In a study by Jha et al. (2019), the impact of changing extreme climatic conditions on the productivity over 25 river basins and 10 vegetation types in India was executed, and the resiliency of these ecosystems to sustain the extreme disturbances was evaluated. The result of this study detected 15 out of 25 river basins at high risk, while the terrestrial ecosystems of only 5 river basins were resilient to extreme changes in climatic conditions. Regarding vegetation types, the study by Jha et al. (2019) found only 2 out of 10, as resilient to extreme changes in climatic conditions.

According to the Economics of Land Degradation (ELD Initiative (Economics of Land Degradation Initiative) 2015) initiative, the land degradation is estimated to affect more than 25% (37.3 million km^2) of land area across the globe. While according to Huang et al. (2015), the developing countries account for approximately 40% land degradation, experience 78% of the projected global dryland expansion, and 50% of the population growth by the year 2100. Consequently, the impacts of climate change to biodiversity, crop production and livelihood are also high in these developing dryland areas (IPCC (Intergovernmental Panel on Climate Change) 2014). Gisladottir and Stocking (2005) emphasized that the land degradation increases sensitivity of agroecological ecosystems to the impacts of climatic changes leading to reduction in their resilience and adaptive capacity. The ecosystem services provided by the agroecological systems is potentially determined by the way these systems are managed, while for innovative management and policy options, it is necessary to understand the impact of climate change and land degradation on resilience of these systems (Webb et al. 2017).

The ecosystem attributes of species diversity and connectivity are commonly considered to provide resilience because they apply to a wide variety of species and ecosystems (Timpane-Padgham et al. 2017). Plant diversity within agroforestry landscapes can support crop yields and enhance agricultural resilience. Diversity, especially genetic and functional diversity, is one of the principal sources of resilience, providing a strong justification to maintain diversity (Bos et al. 2007; Hulvey et al. 2013). The integration of commodity crops such as coffee, cacao and rubber with trees, or in forest mosaics can increase production by providing regulating services (Ricketts et al. 2014; Priess et al. 2007). Agroforestry can also sustain agricultural intensification by regulating ecosystem functions such as nutrient recycling, microclimate modification, water-use efficiency, species diversity, reduced agrochemical pollution (Barrios et al. 2012; Bayala et al. 2014; Vaast and Somarriba 2014).

Intraspecific diversity within species is a contributor of ecosystem functioning by increasing productivity and stability of plant populations (Carroll et al. 2014). However, more research is needed to systematically design agroforestry systems that incorporate functionally important tree species and genotypes with staple and annual crops in diverse planting regimes to create mixtures that generate higher levels of multiple desired functions and services. There is need for a greater understanding of how agroforestry mechanisms can diversify agroecosystems at species level and bring about direct benefits and resilience in specific aspects of agricultural production is key (Carsan et al. 2014). These aspects have applications for agroforestry systems as their functioning depends on interaction and management of both the diversity of species present in landscapes and the genetic variation within these species.

5.5.1 Criteria and Indicators for Assessing Resilience of Agroforestry Practices

A set of criteria and indicators could be used for assessing the resilience of agroforestry practices. Martini et al. (2020) have discussed several quantitative and qualitative methods for assessing the resilience of the implemented agroforestry practices in Southeast Asia. Some selected indicators which are simple, measurable, achievable, replicable, and time bound are summarized in Table 5.3.

Agroforestry can play an important role in improving resilience under uncertain climates through microclimate buffering and regulation of water flow (Nguyen et al.

Table 5.3 Examples of criteria and indicators for resilient agroforestry practices (Adapted from Martini et al. 2020)

Criterion	Indicator	Possible measure
Conservation	• Reduction in soil erosion • Increase in soil fertility • Water availability in dry seasons	• Amount of soil loss per ha per year • Soil organic matters/nutrient content • Amount of water for crops and humans
Productivity	• Increase in crop/livestock yields • Increase in productivity of farmland	• Yields of crops, livestock harvested per land unit per year • Land equivalent ratio
Diversity	• Inclusion of various species • Existence of tree, crop, livestock products at different times • Existence of various income sources	• Number of tree/crop/animal species • Different tree, crop, livestock products produced throughout the year • Incomes from trees, crops, livestock
Adaptability	• Change in microclimate • Frequency of disease/pest (outbreak) • Damage/loss of trees, crops, animals owing to climatic stress • Recovery periods after stresses	• Temperatures, humidity over a period • Incidence of diseases/pests in a period • Damage/mortality rate of trees, crops, animals • Time (e.g. months) needed to recover

2013). This study shows that diversity of agroforestry systems provides multiple benefits and secure assets for farmers all year round if well managed. The authors present appraisal methods to assess priority species and community vulnerability, which could be useful to develop adaptation options in agroforestry landscapes. Agroforestry facilitates flexible responses to rapid shifts in ecological conditions, while at the same time maintaining or restoring soil and water resources (Molua 2005; Du-Toit et al. 2004). Tewari et al. (2014) and Soni et al. (2017) reported manyfold increase in SOC, micronutrients and crop yield under *Prosopis cineraria* in both silvopastoral and silviagricultural systems and the air temperature was lower up to 2 °C under the tree canopies in dry regions in India. The trees harvested the nutrients and moisture from deeper layers making these available to crops. For more details related to soil amelioration, nutrient and moisture availability and climate resilience under agroforestry systems, see chapter by Sileshi et al. (2022) in this publication.

As described by Martini et al. (2020), vegetables and medicinal plants under shade of *Erythrina lithosperma*, *Leucaena glauca*, *Paraserianthes falcata* and various species of fruit trees are grown by farmers *in* multi-strata coffee cropping system in Southeast Asia. At farm level, trees provide multiple benefits, whereas at landscape level, the multi-strata coffee could lead to positive land-use change, bringing many environmental benefits, such as controlled erosion and decreased sediment, increased biodiversity, increased carbon stock, water regulation and forest protection, helping to increase the resilience of the watershed landscape to predicted climatic issues, particularly increasing hot temperatures.

Agroforestry contributes to climate resilience through diversification of agricultural production (Xu et al. 2014; Jat et al. 2016; Lin et al. 2021), and providing benefits to farmers at different times of the year, thereby, reducing the risk of crop failure and food shortages or insecurity when facing climatic stressors. Intensive silvopastoral systems with an overstorey of shrubs and trees are resilient, allowing for continuous availability of fodder (Altieri et al. 2015). Agroforestry has become a part of a climate change response by adapting to increased risks and uncertainties, facilitating capture and storage of carbon and restoring landscape multi-functionality which allows current human resource appropriation to become sustainable (van Noordwijk et al. 2018; Catacutan et al. 2017).

5.6 Increased Potential for Carbon Sequestration

Agroforestry systems present the ideal opportunity for increased C sequestration within tree biomass and soils (Rosenstock et al. 2019) as woody perennials can assimilate atmospheric CO_2 and store C in above- and belowground parts of plants. Soil carbon sequestration in AFS constitutes an important factor for increasing resilience to climate change threats Carbon sequestration in agroforestry systems in degraded landscapes have been comprehensively investigated in a number of studies (see Mbow et al. 2014a, b; Dagar et al. 2020a, b; Catacutan et al. 2017), which are briefly described as follows:

5.6.1 Aboveground and Total Carbon Stock in Agroforestry Systems

Global agricultural land is about 10% with a carbon stock of about 3–18 Mg C ha^{-1} (Zomer et al. 2009). In Africa, tree densities in farming landscapes range from low cover of about 5% in the Sahel to more than 45% in humid tropical zones where cocoa, coffee and palm oil agroforestry systems prevail (Zomer et al. 2009) and in sub-Saharan Africa, 15% of farms have tree cover of at least 30%. This points to a high potential in Africa for sequestering carbon and reducing other agriculture-related GHG emissions, particularly in farm land that currently has low tree cover. In Africa, agroforestry systems such as *Faidherbia albida* dominated parklands, rotational woodlots, tree planting-wind-rows-home gardens, long-term fallows, regrowth of woodlands in abandoned farms, AFS and integrated land use could sequester about 0.50–3.9 Mg C ha^{-1} year^{-1} carbon in the biomass and the total carbon stock in agroforestry systems averaged 15.7–77.9 Mg C ha^{-1} (Mbow et al. 2014a, b) (Table 5.4).

According to Kandji et al. (2006), the carbon sequestration potential of agrosilvicultural systems in humid tropical ecoregions ranged from 12 and 228 Mg C ha^{-1}. Carbon sequestration and storage potential of common agroforestry practices in Indonesia, Philippines and Vietnam in Southeast Asia are given in Table 5.4. Total organic carbon stock ranged from 46.8 to 209 Mg C ha^{-1}, whereas aboveground carbon stock was 14.35–163 Mg C ha^{-1}. It is evident that almost all agroforestry practices, except alley cropping, can sequester a significant amount of carbon in aboveground and the total system (Table 5.4). Tolentino et al. (2010) found that complex agroforestry systems had a carbon stock of 192 Mg C ha^{-1}, which is almost three times more than the carbon stock of tree plantations (59 Mg C ha^{-1}). Multi-strata cacao-agroforestry systems in Indonesia and the Philippines have been shown to hold stock above 100 Mg C ha^{-1} for aboveground carbon (Lasco et al. 2001; Santhyami et al. 2018). If agroforestry systems in Vietnam were expanded to their potential of an additional 10 million ha, at least 260 Mt C could be sequestered annually (Mulia et al. 2018, 2020).

Roshetko et al. (2002) estimated the aboveground carbon stock of Indonesian home gardens at 30–123 Mg of carbon per hectare with an average of 35.3 Mg C ha^{-1} at 13 years, which corresponds to carbon stock found in similarly aged secondary forests (Kumar 2006). Furthermore, the carbon-sequestration potential of home gardens mimics the structure and diversity of mature evergreen forest that is comparable to forest stands (Kumar 2006).

In Sabah, Malaysia, Besar et al. (2020) reported higher aboveground carbon stock in oil-palm agroforestry systems ranging 35.51–39.01 Mg C ha^{-1}, whereas it was 14.35–33.19 Mg C ha^{-1} for monocultures (Table 5.5). Total ecosystem carbon stock in oil-palm agroforestry systems ranged 78.28–85.40 Mg C ha^{-1} for agroforestry systems, whereas it was 60.30–76.44 Mg C ha^{-1} for monocultures. Thus, adopting agroforestry can also avoid agricultural expansion into, and wood extraction from, intact natural forests (Guillaume et al. 2018). It was found that the conversion of

Table 5.4 Carbon sequestration potential of some agroforestry systems in Africa and Southeast Asia (Source Mbow et al. 2014 and references therein, Catacutan et al. 2017; Besar et al. 2020)

Country/agroforestry system/ maximum rotation period	Agroforestry component	Carbon stock (Mg C ha^{-1})	Sources
Africa			
Parklands dominate AFS (*Faidherbia albida*)/50 year rotation	Total stock	33.4 (5.7–70.8)	Based on Mbow et al. (2014a, b)
Rotational woodlots/5year rotation	Total stock	18.5 (11.6–25.5)	-do-
Tree planting-wind-rows-home gardens/ 25year rotation	Total stock	19.0 [ns]	-do-
Long term fallows, regrowth of woodlands in abandoned farms/25year rotation	Total stock	15.7 [ns]	-do-
AFS and integrated land use/50year rotation	Total stock	77.9 [12–228]	-do-
South-east Asia			
Malaysia			
Agroforestry system of oil palm + agarwood (Aquilaria alaccensis), Tawau City, Sabah	Aboveground, 5–27 years; Soil (0–30 cm)	35.51–39.01 (39.12–49.75)	Besar et al. (2020)
Monoculture oil palm plantation, Tawau City, Sabah	Aboveground, 6–16 years; Soil (0–30 cm)	14.35–33.19 (43.09–45.46)	Besar et al. (2020)
Indonesia			
Home gardens in Sumatra	Aboveground, 12–17 years	55.8–163	Kumar (2006)
Simple systems; complex systems	Total stock	130; 209	Wardah et al. (2011)
Philippines			
Taungya agroforestry systems; Mixed multi-storey systems; *Albizia falcataria* and coffee multi-story systems	Total stock	174–162–92	Labata et al. (2012)
Leucaena leucocephala fallow	Aboveground, 6-years cycle	16	Lasco and Pulhin (2009)
Alley cropping	Aboveground	1.5	Lasco et al. (2010)
Coconut-based multi-story systems; multi-story systems	Aboveground	39; 116	Lasco et al. (2010)
Vietnam			
Home gardens; fruit gardens	Total stock	69.6, 46.8	Nguyen et al. (2011)

Table 5.5 C sequestration capacity of various agroforestry systems in West Java province (adapted from Siarudin et al. 2021, and references therein)

Agroforestry system	Total aboveground C stock (Mg ha^{-1})
Manglid + cardamom (Tasikmalaya)	44 (16.7–108)
Gmelina + cardamom (Tasikmalaya, banjar, pangandaran)	63.7 (20.3–114.4)
Caddam + cardamom (Garut)	37.0
Caddam + elephant grass (Garut)	37.0
Mixed-tree species and fresh-water fishpond (Ciamis)	54.0 (12.8–89.2)
Mixed tree lots (Ciamis)	108.9 (86.3–123.4)

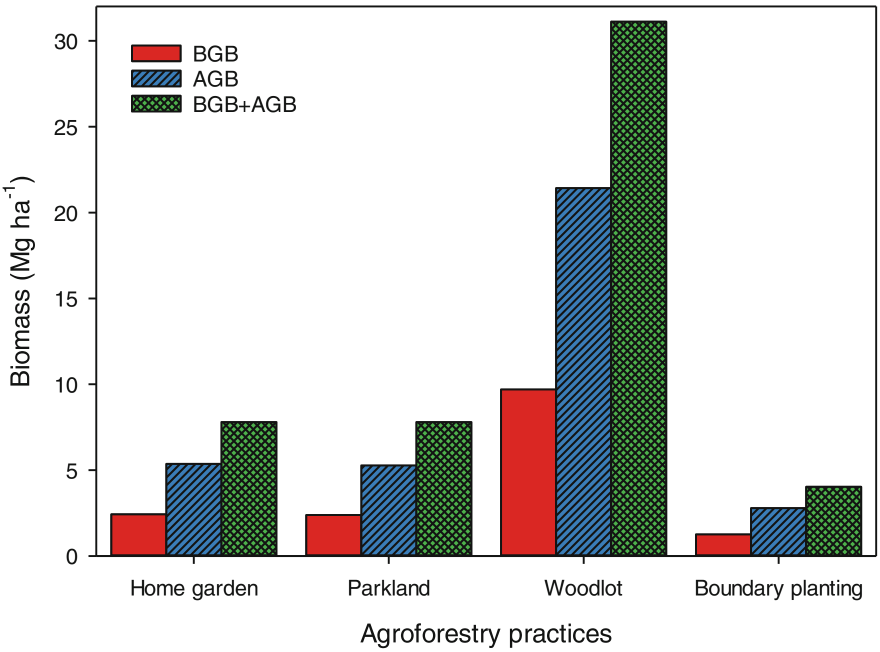

Fig. 5.3 Mean biomass carbon stock in agroforestry system Mg ha^{-1}) for different agroforestry practices. *BGB* belowground biomass, *AGB* aboveground biomass (based on data from Manaye et al. 2021)

tropical rainforest to rubber agroforests or jungle rubber with no fertilizer or herbicide applications reduces the release of CO_2 by 27% (Guillaume et al. 2018), and if all rubber plantations in Southeast Asia were under agroforestry systems, there would be large potential of CO_2 mitigation (Guillaume et al. 2018).

Recently, Manaye et al. (2021) studied tree diversity and carbon stocks in four AF practices (home garden, parkland, boundary plantation and woodlot) in northern Ethiopia. These workers reported greater species richness in home garden and parkland AF systems than in woodlots. Total aboveground biomass ranged from 2.78 to 21.43 Mg ha^{-1} in the four AF practices (Fig. 5.3) while total belowground biomass C stock ranged from 1.26 to 9.70 Mg ha^{-1}. The total biomass C and the soil organic carbon stock (0–60 cm) ranged from 77 to 135 Mg C ha^{-1}. Total biomass C stocks were positively and significantly related with Shannon diversity index. SOC stock increased with increasing species richness and Shannon diversity index in all four AF systems (Manaye et al. 2021). The study suggested agroforestry to be a very important means of storing carbon.

Cyamweshi et al. (2021) reported that biomass carbon increased with tree size, from 7.1 Mg C ha^{-1} in 3-year-old trees to 34.4 Mg C ha^{-1} in 10-year-old trees and biomass carbon decreased with increasing elevation from 21.4 Mg C ha^{-1} at lower elevations (2011–2110 m) to 9.6 Mg C ha^{-1} in the high elevation (> 2510 m). *Alnus nepalensis*-based agroforestry significantly contributes to carbon sequestration, although the magnitude of these benefits varies with tree age and elevation Planting *Alnus* trees on farms can meet local needs for stakes for climbing beans, wood and soil fertility improvement, as well as the global need for regulation of climate change.

Agroforestry systems practised by smallholder farmers is an important option for restoring degraded land and associated ecosystem functions in West Java, Indonesia (Siarudin et al. 2021). Six agroforestry systems were that of Gmelina (*Gmelina arborea*) + cardamom (*Amomum compactum*); manglid (*Magnolia champaca*) + cardamom; caddam (*Neolamarckia cadamba*) + cardamom; caddam + elephant grass (*Pennisetum purpureum*); mixed-tree + fishpond and mixed-tree lots. This study showed that the mixed-tree system practised in the Ciamis area was found to have the highest C stock potential, i.e. 108.9 Mg ha^{-1}, while the caddam-based system with cardamom or elephant grass practised in Garut provides the lowest C stock (37 Mg ha^{-1}) (Table 5.5). These systems were found to be effective to prevent soil erosion and help to restore degraded land.

Reang et al. (2021) studied the tree diversity and ecosystem carbon storage in a chronosequence from swidden agriculture through different phases of pineapple (*Ananas comosus*) agroforestry systems (PAFS) in the rural landscape in the Indian Eastern Himalayas (Table 5.6). The most dominant species in the native forests was *Palaquium polyanthum*, while agricultural land use and PAFS aged <5, 11–15 and >15 years old were dominated by *Gmelina arborea*, *Albizia procera*, *Areca catechu* and *Hevea brasiliensis*, respectively. The ecosystem carbon storage showed a 30% decrease from 261.43 Mg C ha^{-1} in native forests to 181.07 Mg C ha^{-1} in <5-year-old PAFS (Table 5.6). This study has indicated that traditional PAFS maintains a steady ecosystem carbon stock while reducing land use related carbon emission and providing additional co-benefits to the communities.

According to Lin et al. (2021), different studies of Asian agroforestry systems show that they can sequester 2–10 Mg CO_2e ha^{-1} year^{-1}. The total carbon stock of agroforestry ranges between 4 and 23 Mg CO_2e ha^{-1} year^{-1} for aboveground biomass, 1 and 4 Mg CO_2e ha^{-1} year^{-1} for belowground biomass, and 1 and 14 Mg CO_2e ha^{-1} year^{-1} in soils.

Table 5.6 Ecosystem carbon storage in native forest, agriculture and pineapple-based agroforestry system (PAFS) in North East India (source Reang et al. 2021)

Land use	Total carbon storage in trees (Mg C ha^{-1})	Total carbon storage in pineapple (Mg C ha^{-1})	SOC stock (Mg C ha^{-1})	Ecosystem carbon storage (Mg C ha^{-1})
Native forest	79.67	–	181.76	261.43
Agriculture	13.68	–	188.92	202.60
<5 years PAFS	12.37	15.87	152.83	181.07
5–10 years PAFS	33.24	28.25	157.32	218.81
11–15 years PAFS	35.14	31.66	168.49	235.29
>15 years PAFS	38.99	32.82	175.65	247.46

5.6.2 Soil Carbon Sequestration

Soils play a major role even in the global C cycle, and the soil C pool comprises soil organic C (SOC) estimated at 1550 Pg (1 pg = 10^{15} g = 1 billion tons) and soil inorganic C about 750 Pg, both pools to 1-m depth (Batjes 1996). This total soil C pool of 2300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg; a reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppm (Lal 2001). Thus, any change in soil C pool would have a significant effect on the global C budget. Several authors have suggested that AFS have higher potential to sequester C than pastures and field crops (Roshetko et al. 2002; Sharrow and Ismail 2004; Kirby and Potvin 2007). This is based on the notion that tree incorporation in croplands and pastures would result in greater net sequestration of C both above- and belowground (Haile et al. 2008; Nair et al. 2009a). In a feasibility appraisal, Nair et al. (2009b) concluded that agroforestry systems have a higher potential to sequester C than pastures, or field crops, because tree incorporation in croplands and pastures would result in greater net aboveground as well as belowground C sequestration. However, the methodological difficulties, in estimating C stock of biomass and the extent of soil C storage under varying conditions, are serious limitations in exploiting this low-cost environmental benefit of agroforestry.

Over the last two decades, the issue of global warming has paved the way for new research in agroforestry systems, with a large number of research papers dealing with climate change mitigation through carbon sequestration in soils (see van Noordwijk et al. 2019a, b, c). Recent reviews and meta-analyses suggest that the conversion of arable land to agroforestry systems leads to increased soil organic carbon stocks (Lorenz and Lal 2014; Kim et al. 2016; de Stefano and Jacobson 2018; Cardinael et al. 2018; Feliciano et al. 2018; Shi et al. 2018). Among these, de Stefano and Jacobson (2018), based on meta-analysis, reported that conversion of agricultural land to agroforestry significantly increased SOC stocks at 0–15, 0–30 and 0–100 cm soil depths. These researchers found that among agroforestry systems, significant increases in SOC stocks occurred at various soil horizons and depths in the land-use change from agriculture to agrisilviculture and silvopasture, pasture/grassland to agrisilvopastoral systems, forest to silvopasture, forest plantation to silvopasture, and uncultivated/other land uses to agrisilviculture (de Stefano and Jacobson 2018). Shi et al. (2018) used a meta-analysis of 427 soil C stock data pairs grouped in four main agroforestry systems (AFS), including alley cropping, windbreaks, silvopasture and home gardens, and evaluated changes in AFS and adjacent control cropland or pasture. In this study, the mean soil C stocks in AFS (one-meter soil depth) were 126 Mg C ha^{-1}, which is 19% more than cropland or pasture.

Hübner et al. (2021) performed a meta-analysis about the SOC sequestration potential of different types of agroforestry systems in China, both in topsoil (0–20 cm) and in subsoil (20–40 cm, 40–60 cm). This meta-analysis showed that agrosilvicultural systems and shelterbelts are effective practices to increase SOC stocks, both in top- and subsoils and especially in the subtropical climate zone. These workers showed that SOC sequestration rates were greatest in shelterbelts, followed by agrosilvicultural systems and silvopastoral systems (Table 5.7). There was vertical stratification in SOC sequestration rates indicating decrease with increasing soil depths. The effect of different types of AFS on C sequestration rates was found to be the most pronounced in the topsoil. The differences in C sequestration rates between AFS can be attributed to the specific characteristics of shelterbelts, silvopastoral and agrosilvicultural systems. The type of agroforestry system, including its initial SOC stock, its soil class and its age were the most important variables regulating SOC sequestration rates. The AFS-type and the initial SOC, soil type plays a decisive role for the efficiency of soil C sequestration by agroforestry (Hübner et al. 2021).

In agroforestry and grassland systems of salt-affected soils in India, soil carbon sequestration potential in 0–30 cm soil layer ranged from 6.839 to 27.09 Mg C ha^{-1} (see Dagar et al. 2001). In agrisilvopastoral systems on sodic soils at Bichhian, north-west India, the soil carbon pool was 13.431 Mg C ha^{-1} in *Prosopis juliflora* + *Desmostachya bipinnata* and 9.621 Mg C ha^{-1}in *Prosopis juliflora* + *Sporobolus marginatus* (Kaur et al. 2002). In grassland and different agroforestry systems on calcareous soils irrigated with saline water in north-west India, the total organic carbon in 0–30 cm soil layer (Mg C ha^{-1}) was: 6.839 in the native grassland, 21.195 in *Acacia nilotica* + *Cenchrus ciliaris* silvopastoral system and 20.181 in *Salvadora persica* + native grass silvopastoral system (Kumari et al. 2018). The integration of trees with forage grasses improved soil organic carbon significantly. The silvopastoral system on moderately alkaline soils (pH 8.36–8.41) at Kachchh, Gujarat sequestered 36.3–60.0% more total soil organic carbon compared to the tree alone and 27.1–70.8% more in comparison to the grass only system (Mangalassery et al. 2014).

Table 5.7 Soil carbon sequestration rates on the basis of meta-analysis of 43 studies in different agroforestry type and three soil depths in China (based on Hübner et al. 2021)

Soil depth	Shelterbelts	Silvopastoral	Agrosilvicultural
	Soil organic carbon sequestration (Mg C ha^{-1} year^{-1})		
Topsoil (0–20 cm)	0.92	0.70	0.23
Subsoil (20–40 cm)	0.72	0.48	0.08
Subsoil (40–60 cm)	0.52	0.43	0.02

In pineapple (*Ananas comosus*) agroforestry systems (PAFS) in the rural landscape in the Indian Eastern Himalayas, Reang et al. (2021) reported that the SOC sequestration rate was 1.52 Mg ha^{-1} year^{-1} (Table 5.6). The SOC sequestration rate of 0.6 Mg ha^{-1} year^{-1} in a 28-year-old agroforestry system was reported from north eastern India (Yadav et al. 2021). The high SOC sequestration in the studied system could be attributed to higher bush density and greater litter production leading to the build-up of more SOC stock. In other studies, the SOC sequestration rate are reported to range 0.06–7 Mg ha^{-1} year^{-1} in agroforestry systems in different regions of the world (see Nath et al. 2021).

Soil carbon sequestration depends on specific properties of the agroforestry system, decomposition rates of above- and belowground litter, the activity of soil organisms. For specific agroforestry practices, with lower tree densities such as alley cropping and parklands systems (Bayala et al. 2014), soil carbon sequestration may be low. However, reliable data on changes in soil C-stock in response to change in quality and quantity of tree cover from various forms of managed forestry and agroforestry systems are needed (Hairiah et al. 2020). For example, soil carbon measurements are affected due to soil compaction after forest-to-agriculture conversion which can partly mask actual changes in soil carbon stock (Hairiah et al. 2020).

5.6.3 Mitigation Options in Agroforestry

Performance of mitigation options in agroforestry will depend on the relative influence of tree species selection and management, soil characteristics, topography, rainfall, agricultural practices, priorities for food security, economic development options, among others. In order to improve carbon sequestration, or to reduce carbon emissions, several options are available, but all are related to development needs of local communities (Mbow et al. 2014a). Agroforestry is a climate change mitigation solution as it can remove significant amounts of GHGs from the atmosphere. Approximately, more than 1.2 billion people (about 20% of world's population) in rural and urban areas of developing countries depend directly on agroforestry practices, their products and services. Agroforestry is considered to be one of the low costs and sustainable technologies for mitigating climate change because of its ability to improve agroecosystem biodiversity and productivity (Goncalves et al. 2021).

Agroforestry also involves practices that raise GHG emissions, such as pasture maintenance by burning, nitrogen fertilization and animal production. In order to optimize agroforestry for adaptation and mitigation to climate change, there is a need for more integrated management to increase benefits and reduce negative impacts on climate (Mbow et al. 2014a). Agroforestry systems are characterized by complexity and diversity along with recycling of resources and have shown to increase resilience to climate change in specific contexts, but widespread adoption of agroforestry is likely to be constrained by market failures, maladapted policies and the paucity of evidence about the performance of agroecological practices (Sinclair et al. 2019).

Chapman et al. (2020) prepared a 30-meter resolution global map of aboveground woody carbon, tree cover and cropland extent, as well as a 1-km resolution map of global pasture land to estimate the current and potential carbon storage of trees in non-forested portions of agricultural lands. These workers estimated that crop lands currently store 3.07 Pg of carbon (C) in aboveground woody biomass (i.e. trees) and pasture lands account for an additional 3.86 Pg C across a combined 3.76 billion ha globally. They have further stated that many countries can meet large portions of their NDCs through the addition of trees in agricultural lands. For example, India's NDC commits to an additional land sector carbon sink of 2.5–3 billion tons CO_2e (0.61–0.73 Pg C) by 2030 (Government of India 2014). Analysis of these workers suggests that a 1% adoption scenario as part of India's National Agroforestry Policy would deliver 30% of this commitment when considering the additional above-ground biomass alone. The mitigation opportunity afforded by agroforestry has not included agroforestry in their NDCs (IUCN 2018). Over 84% of potential additional carbon storage and 53% of potential carbon losses from trees in crop and pasture lands occurs in countries that do not list agroforestry as climate mitigation or adaptation technique (Chapman et al. 2020). The different agroforestry practices characterized by unique carbon density signatures could be analysed using machine learning approaches to map specific agroforestry practices across larger spatial scales so as to provide information about climate change benefits.

5.7 Agroforestry and Climate Change Adaptation

Agroforestry provides many environmental benefits including carbon sequestration, wood energy, improved soil fertility and enhancement of local climate conditions, and reduces human impacts on natural forests. Most of these benefits have direct bearing for local adaptation as well as contributing to control atmospheric greenhouse gas concentrations at a global level (Mbow et al. 2014a, b).

In Vietnam, Nguyen et al. (2013) found that rice and rain-fed crop systems suffered over 40% losses of yields in years of extreme drought or flood compared to tree-based systems. Households with home gardens had a higher adaptive capacity to climate change owing to the resilience of diverse tree species. Likewise, upland smallholders in the Philippines who adopted agroforestry were reportedly experiencing less severe impact from extreme weather events (Landicho et al. 2016).

Microclimatic improvement through agroforestry has a major impact on crop performance as trees can buffer climatic extremes that affect crop growth. More shaded coffee systems have shown to protect crops from decreasing precipitation and reduced soil water availability because the over story tree cover is able to reduce soil evaporation and increase soil water infiltration (Lin et al. 2007). The shading effects of agroforestry trees can buffer temperature reducing exposure to supra-optimal temperatures, under which physiological and developmental processes and yield become increasingly vulnerable (Lott et al. 2009). Scattered trees in agroforestry farms can enhance the understory growth by reducing incident solar radiation, air and soil temperature, while improving water status, gas exchange and water use efficiency (Bayala et al. 2008). Agroforestry systems are examples of agricultural systems with high structural complexity that have been shown to buffer crops from large fluctuations in temperature (Lin 2011), thereby keeping the crop closer to its optimum conditions. Trees in AFS help in improving water productivity through enhancing the effective use of rainfall, of the water stored in the soil, and using the marginal quality water; effective use of nutrients; in-situ soil organic matter enrichment; reduction in excessive transpiration of crops under shade; modifying microclimate including reduction in temperature and increasing humidity; absorption of water from deeper soil horizons beyond the reach of crop rooting zone; fixing nitrogen (leguminous trees); and ameliorating the soil (Dagar et al. 2016a; Soni et al. 2017); therefore, appropriate choice of species (e.g. *Prosopis cineraria* in dry regions of India) is very important for enhancing the productivity of the system through adaptation to climate change.

According to the 2019 update of the IPCC guidelines for national greenhouse gas inventories, two types of climate change adaptation have been identified by the various workers: firstly, an increase in tree diversity in order to be prepared for increased variability and have options available for adaptive management decisions, and secondly, targeted interventions in order to be prepared for a projected trend in conditions (van Noordwijk et al. 2011; De Leeuw et al. 2014; Hoang et al. 2014; Catacutan et al. 2017). Long-term persistence of AF systems in fragile environments such as Sahelian or Mediterranean drylands is based on maintenance of the buffer functions trees and soils protected by trees provide (Bayala et al. 2019). For climate change adaptation, a focus on social learning, germplasm exchange and social-ecological system governance can complement crop breeding and ‘tree improvement’ programmes (Sinclair et al. 2019). There is need to give due consideration to local ethnobotanical knowledge, germplasm exchange and adaptation responses of the whole system (Kmoch et al. 2018).

Bado et al. (2020) assessed the performance of *Ziziphus mauritiana* intercropped with cowpea (*Vigna unguiculata*) and pearl millet, or as sole crops, in Niger. They found that the presence of trees increased millet yields and water use efficiency with the addition of manure or without the addition of mineral fertilization. However, the presence of trees reduced millet yields when mineral fertilizer was applied. These workers indicated that this system is well adapted for low input farming systems, provided there is greater understanding of conditions for the application of mineral fertilizers for enhancing yields under agroforestry.

Borden et al. (2020) provided a detailed analysis of how shade trees, which are used as an adaptation strategy towards climate change, modify soil resource acquisition strategies of cocoa (*Theobroma cacao*). Using a functional trait-based approach and relying on the fine root functional classification that distinguishes between absorptive and transport roots, they studied the combined impact of the presence of shade tree, water availability and soil texture on both types of roots. They found that absorptive root traits in agroforestry systems were significantly more conservative compared to those in monoculture in one climato-edaphic condition, but not in the others, while transport roots were more affected by soil texture. Borden et al. (2020) emphasized that agroforestry's success as a climate change adaptation strategy in cocoa systems requires detailed understanding of crop response strategies under different pedoclimatic conditions.

According to van Noordwijk et al. (2021), agroforestry-based adaptation to global climate change can consist of (1) reversal of negative trends in diverse tree cover as generic portfolio risk management strategy; (2) targeted, strategic, shift in resource capture to adjust to changing conditions (e.g. lower or more variable rainfall, higher temperatures); (3) vegetation-based influences on rainfall climatic; or (4) adaptive, tactical, management of tree-crop interactions based on weather forecasts for the following growing season. These workers have reviewed recent literature to assess current levels of uncertainty in climate adaptation assessments in and through AF.

In a recent editorial (Agriculture, Ecosystems and Environment), Cardinael et al. (2021) have highlighted that agroforestry systems play a key role in climate change mitigation as well as adaptation to climate change. They argued that climate change mitigation is primarily concerned with the reduction of greenhouse gas (CO_2, CH_4, N_2O) emissions and increased carbon sequestration. The two policy agendas (mitigation and adaptation) interact because carbon, nitrogen and hydrology are closely linked. This is why agroforestry has a long-standing recognition of playing a key role in approaching mitigation and adaptation, or 'mitigadaptation' (van Noordwijk et al. 2011).

5.8 Conclusions

Land degradation is a pervasive challenge to human societies, driven mostly by socio-economic and environmental factors. Climate change is expected to increase degradation processes in forest, grassland and agricultural systems of developing countries, particularly Asia and Africa because of increasing demands for food, energy and feed for the livestock. There are synergies existing between international policies and goals related to ecosystem restoration. This review shows that agroforestry can provide viable restoration pathways for highly degraded lands with very low soil fertility. This review also showed that agroforestry offers the option to increase carbon storage to mitigate the effect of climate change, while playing an important role in restoration of degraded landscapes. For agroforestry to succeed, it requires a systems perspective that can be readily integrated into landscape approaches. At the field scale, agroforestry interventions can play an important role in improving soil health, conserving biodiversity and providing minor forest produce, while minimizing negative interactions between trees and crops. The restoration of degraded landscapes using agroforestry can increase the resilience of communities to shocks, including drought and food shortages, and help mitigate climate change. Agroforestry has real potential to contribute to food security, climate change mitigation and adaptation, while protecting the environmental resource base of many degraded tropical landscapes. For millions of farmers in developing countries whose livelihoods are threatened by climate change and land degradation, agroforestry offers a pathway towards climate change mitigation and adaptation.

References

Agroforestry Network, Vi-skogen (2018) Scaling up agroforestry potential, challenges and barriers: A review of environmental, social and economic aspects at the farmer, community and landscape levels. Commissioned by the Agroforestry Network and its partners Agroforestry Sverige, Focali, NIRAS, SIANI, SLU Global, SwedBio at Stockholm Resilience Centre and Vi-skogen

Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. Agron Sustain Dev 35:869–890

Anjos LJS, de Toledo PM (2018) Measuring resilience and assessing vulnerability of terrestrial ecosystems to climate change in South America. PLoS ONE 13(3):e0194654. https://doi.org/10.1371/journal.pone.0194654

Bado BV, Whitbread A, Laminou M, Manzo S (2020) Improving agricultural productivity using agroforestry systems: performance of millet, cowpea, and *Ziziphus*-based *Ziziphus*-based cropping systems in West Africa Sahel. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2020.107175

Bai ZG, Dent DL, Olsson L, Schaepman ME (2008) Global assessment of land degradation and improvement. 1. Identification by remote sensing. ISRIC–World Soil Information, Wageningen

Barrios E, Sileshi GW, Shepherd KD, Sinclair F (2012) Agroforestry and soil health: linking trees, soil biota and ecosystem services. In: Wall DH (ed) The Oxford handbook of soil ecology and ecosystem services. Oxford University Press, Oxford, pp 315–330

Bastin JF, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner CM, Crowther TW (2019) The global tree restoration potential. Science 365:76–79

Batjes NH (1996) The total carbon and nitrogen in soils of the world. Eur J Soil Sci 47:151–163

Bayala J, Heng LK, Ouedraogo SJ, Noordwijk MV (2008) Hydraulic redistribution study in two native tree species of agroforestry parklands of West African dry savanna. Acta Oecol 34(3): 370–378

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Bayala J, Sanou J, Bazié HR, Coe R, Kalinganire A, Sinclair FL (2019) Regenerated trees in farmers' felds increase soil carbon across the Sahel. Agrofor Syst. https://doi.org/10.1007/s10457-019-00403-6

Beckley BD, Callahan PS, Hancock DW, Mitchum GT, Ray RD (2017) On the "cal-mode" correction to TOPEX satellite altimetry and its effect on the global mean sea level time series. J Geophys Res Oceans 122:8371–8384. https://doi.org/10.1002/2017JC013090

Beer J, Muschler R, Kass D, Somarriba E (1998) Shade management in coffee and cacao plantations. Agrofor Syst 38:139–164. https://doi.org/10.1007/978-94-015-9008-2_6
Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecol Lett 15:365–377
Besar NA, Suardi H, Phua MH, James D, Mokhtar MB, Ahmed MF (2020) Carbon stock and sequestration potential of an agroforestry system in Sabah, Malaysia. Forests 11(2):210
Bhaga TD, Dube T, Shekede MD, Shoko C (2020) Impacts of climate variability and drought on surface water resources in Sub-Saharan Africa using remote sensing: a review. Remote Sens 12: 4184
Borden KA, Anglaaere LCN, Owusu S, Martin AR, Buchanan SW, Addo-danso SD, Isaac ME (2020) Soil texture moderates root functional traits in agroforestry systems across a climatic gradient. Agric Ecosyst Environ 295:106915
Bos MM, Steffan-Dewenter I, Tscharntke T (2007) The contribution of cacao agroforests to the conservation of lower canopy ant and beetle diversity in Indonesia. Biodivers Conserv 16(8): 2429–2444
Brenner AJ (1996) Microclimate modifications in agroforestry. In: Ong CK, Huxley P (eds) Tree-crop interactions - a physiological approach. CAB International, Wallingford, pp 319–364
Bridges EM, Oldeman LR (1999) Global assessment of human induced soil degradation. Arid Soil Res Rehabil 13(4):319–325
Cardinael R, Umulisa V, Toudert A, Olivier A, Bockel L, Bernoux M (2018) Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environ Res Lett 13:124020
Cardinael R, Cadisch G, Gosme M, Oelbermann M, van Noordwijk M (2021) Climate change mitigation and adaptation in agriculture: why agroforestry should be part of the solution. Agric Ecosyst Environ 319:107555
Carroll SP, Jørgensen PS, Kinnison MT et al (2014) Applying evolutionary biology to address global challenges. Science 346:313–324
Carsan S, Stroebel A, Dawson I, Kindt R, Mbow C, Mowo J, Jamnadass R (2014) Can agroforestry option values improve the functioning of drivers of agricultural intensification in Africa? Curr Opin Environ Sustain *6*:35–40
Catacutan DC, van Noordwijk M, Nguyen TH, Öborn I, Mercado AR (2017) Agroforestry: contribution to food security and climate-change adaptation and mitigation in Southeast Asia. World Agroforestry Centre (ICRAF), Bogor
Catacutan DC, Finlayson RF, Gassner A, Perdana A, Lusiana B, Leimona B, Simelton E, Born I, Galudra G, Roshetko JM, Vaast P, Mulia R, Lasco RL, Dewi S, Borelli S, Yasmi Y (2018) ASEAN guidelines for agroforestry development. Association of South-East Asian Nations. Jakarta, ASEAN Secretariat
Chapman M, Walker WS, Peter SCC, Farina M, Griscom BW, Baccini A (2020) Large climate mitigation potential from adding trees to agricultural lands. Glob Chang Biol 26(8):4357–4365. https://doi.org/10.1111/gcb.15121
Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460
Chazdon R, Brancalion P (2019) Restoring forests as a means to many ends. Science 365:24–25
Ciais P, Sabine C, Bala G et al (2013) Carbon and other biogeochemical cycles. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
Crippa M, Solazzo E, Guizzardi D, Monforti- Ferrario F, Tubiello FN, Leip A (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 8:1–12
Cyamweshi AR, Kuyah S, Mukuralinda A et al (2021) Potential of *Alnus acuminata* based agroforestry for carbon sequestration and other ecosystem services in Rwanda. Agrofor Syst 95:1125–1135. https://doi.org/10.1007/s10457-021-00619-5

Dagar JC, Gupta SR (2017) Agroforestry: potentials for rehabilitation of degraded lands, constraints and the way forward. In: Dagar JC, Tewari JC (eds) Agroforestry research development. Nova Science, Washington, pp 47–97
Dagar JC, Gupta SR (2020) Agroforestry interventions for rehabilitating salt-affected and waterlogged marginal landscapes. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 2. Springer, Singapore, pp 111–162
Dagar JC, Minhas PS (eds) (2016) Agroforestry for the management of waterlogged saline soils and poor-quality waters. In: Advances in agroforestry, vol 13. Springer, New Delhi, p 210
Dagar JC, Singh AK (eds) (2018) Ravine lands: greening for livelihood and environmental security. Springer, Singapore, p 636
Dagar JC, Tewari VP (eds) (2017) Agroforestry: anecdotal to modern science. Springer, Singapore, p 879
Dagar JC, Singh G, Singh NT (2001) Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali soils in India. Arid Land Res Manag 15:115–133
Dagar JC, Singh AK, Arunachalam A (eds) (2014a) Agroforestry systems in India: livelihood security and environmental services. In: Agroforestry systems in India: livelihood security and ecosystem services. Springer, New Delhi, p 400
Dagar JC, Pandey CB, Chaturvedi CS (2014b) Agroforestry: a way forward for sustaining fragile coastal a and island agro-ecosystems. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and ecosystem services, Advances in Agroforestry, vol 10. Springer, New Delhi, pp 185–232
Dagar JC, Lal K, Kumar M, Ram J, Chaudhari SK, Yadav RK, Singh G, Ahamad S, Kaur A (2016a) Impact of eucalyptus geometry on biomass production, water table drawdown, carbon sequestration and inter-crop yield on waterlogged saline soils of North-West India. Agric Ecosyst Environ 233:33–42
Dagar JC, Yadav RK, Tomar OS, Minhas PS, Yadav G, Lal K (2016b) Fruit-based agroforestry systems for saline water-irrigated semi-arid hyperthermic camborthids soils of north-west India. Agrofor Syst 90:1123–1132
Dagar JC, Yadav RK, Sharma PC (eds) (2019) Research developments in saline agriculture. Springer, Singapore, p 926
Dagar JC, Gangaiah B, Gupta SR (2020a) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, pp 367–424
Dagar JC, Gupta SR, Teketay D (eds) (2020b) Agroforestry for degraded landscapes: recent advances and challenges. Springer, Singapore, p 554
De Leeuw J, Njenga M, Wagner B, Iiyama M (eds) (2014) Treesilience, an assessment of the resilience provided by trees in the dry lands of Eastern Africa. World Agroforestry Center, ICRAF, Nairobi, p 166
de Stefano A, Jacobson MG (2018) Soil carbon sequestration in agroforestry systems: a meta-analysis. Agrofor Syst 92:285–299
Dhyani S, Kadaverugu R (2020) Food security and cultural benefits from urban green spaces: exploring urban foraging as a silently growing global movement. Clim Change Environ Sustain 8:219–225
Dhyani S, Murthy IK, Kadaverugu R, Dasgupta R, Kumar M, Adesh Gadpayle K (2021) Agroforestry to achieve global climate adaptation and mitigation targets: are south Asian countries sufficiently prepared? Forests 12:303
Diamond J (2005) Collapse: how societies choose to fail or succeed. Viking, New York
Duarte EMG, Cardoso IM, Stijnen T, Mendonça MAFC, Coelho MS, Cantarutti RB, Kuyper TW, Villani EMA, Mendonça ES (2013) Decomposition and nutrient release in leaves of Atlantic rainforest tree species used in agroforestry systems. Agrofor Syst 87:835–847

Duguma LA, Minang PA, Mpanda M, Kimaro A, Alemagi D (2015) Landscape restoration from a social-ecological system perspective? In: Minang PA, van Noordwijk M, Freeman OE, Mbow C, de Leeuw J, Catacutan D (eds) Climate-smart landscapes: multifunctionality in practice. World Agroforestry Centre (ICRAF), Nairobi, pp 63–73
Du-Toit JT, Walker BH, Campbell BM (2004) Conserving tropical nature: current challenges for ecologists. Trends Ecol Evol 19:12–17
Eckstein D, Kunzel V, Schafer L, Winges M (2019) Global climate risk index 2020: who suffers most from extreme weather events? Weather-related loss events in 2018 and 1999 to 2018
ELD Initiative (Economics of Land Degradation Initiative) (2015) The value of land: prosperous lands and positive rewards through sustainable land management. http://bit.ly/2gQrF87
Epple C, Dunning E (2014) Ecosystem resilience to climate change: what is it and how can it be addressed in the context of climate change adaptation? Technical report for the Mountain EbA Project. UNEP World Conservation Monitoring Centre, Cambridge
Eswaran H, Lal R, Reich PF (2001) Land degradation: an overview. Oxford Press, Khon Kaen
FAO and ITPS (2015) Status of the world's soil resources (SWSR) – main report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome
Farrell CA, Aronson J, Daily GC, Hein L, Obst C, Woodworth P, Stout JC (2021) Natural capital approaches: shifting the UN Decade on Ecosystem Restoration from aspiration to reality. Restor Ecol 2021:13613
Feliciano D, Ledo A, Hillier J, Nayak DR (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254:117–129
Foden WB, Butchart SH, Stuart SN, Vié J-C, Akçakaya HR, Angulo A et al (2013) Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. PLoS One 8(6):e65427
Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L et al (2004) Regime shifts, resilience, and biodiversity in ecosystem management. Annu Rev Ecol Evol Syst 35:557–581
Frederikse T, Landerer F, Caron L et al (2020) The causes of sea-level rise since 1900. Nature 584: 393–397
FSI (2015) India state of forest report. Ministry of Environment & Forests, Dehradun
Fuller DO, Ottke C (2002) Land cover, rainfall and land-surface albedo in West Africa. Clim Chang 54:181–204
Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J, Hua F, Echeverría C, Gonzales E, Shaw N, Decleer K, Dixon KW (2019) International principles and standards for the practice of ecological restoration. Restor Ecol 27: S1–S46
Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A et al (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Secur 2: 197–214
Geist HJ, Lambin EF (2004) Dynamic causal patterns of desertification. Bioscience 54(9):817
Getahun E (2020) A tale of an enclosure: an Ethiopian success story. World Agroforestry (ICRAF), Nairobi
Gibbs HK, Salmon JM (2015) Mapping the world's degraded lands. Appl Geogr 57:12–21
Girvetz E, Ramirez-Villegas J, Claessens L, Lamanna C, Navarro-Racines C, Nowak A et al (2019) Future climate projections in Africa: where are we headed? In: Rosenstock T, Nowak A, Girvetz E (eds) The climate-smart agriculture papers. Springer, Cham, pp 15–27. https://doi.org/10.1007/978-3-319-92798-5_5
Gisladottir G, Stocking M (2005) Land degradation control and its global environmental benefits. Land Degrad Dev 16:99–112
Gomes LC, Bianchia FJJA, Cardoso IM, Fernandes RBA, Fernandes Filho EI, Schulte RPO (2020) Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. Agric Ecosyst Environ 294:106858

Goncalves N, Andrade D, Batista A, Cullen L, Souza A, Gomes H et al (2021) Potential economic impact of carbon sequestration in coffee agroforestry systems. Agrofor Syst 95:419–430

Grimm NB et al (2013) The impacts of climate change on ecosystem structure and function. Front Ecol Environ 11:474–482

Guillaume T, Kotowska MM, Hertel D, Knohl A, Krashevska V, Murtilaksono K, Scheu S, Kuzyakov Y (2018) Carbon costs and benefits of Indonesian rainforest conversion to plantations. Nat Commun 9(1):1–11

Gunderson L (2000) Ecological resilience in theory and application. Annu Rev Ecol Syst 31:425–439

Gupta SR, Dagar JC (2017) Enhancing environmental services of salt-affected soils through agroforestry. In: Dagar JC, Tewari JC (eds) Agroforestry research development. Nova Science, Washington, pp 209–244

Gupta SR, Dagar JC, Jangra R, Asha G (2019) Tree-based systems for enhancing environmental services of saline environments. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer, Singapore, pp 461–499

Haile SG, Nair PKR, Nair VD (2008) Carbon storage of different soil-size fractions in Florida silvopastoral systems. J Environ Qual 37:1789–1179

Hairiah K, van Noordwijk M, Sari RR, Saputra DD, Suprayogo D, Kurniawan S, Prayogo C, Gusli S (2020) A soil carbon stocks in Indonesian (agro) forest transitions: Compaction conceals lower carbon concentrations in standard accounting. Agric Ecosyst Environ 294:106879

Hansen LJ, Biringer JL, Hoffman J (2003) Buying time: a user's manual for building resistance and resilience to climate change in natural systems. WWF, Washington

Hanson C, Buckingham K, Dewitt S, Laestadius L (2015) The restoration diagnostic: a method for developing forest landscape restoration strategies by rapidly assessing the status of key success factors. World Resources Institute, Washington

Hare JA, Morrison WE, Nelson MW, Stachura MM, Teeters EJ, Griffis RB et al (2016) A vulnerability assessment of fish and invertebrates to climate change on the Northeast US continental shelf. PLoS One 11(2):e0146756

Hijioka Y, Lin E, Pereira JJ et al (2014) Asia. In: Barros VR et al (eds) Climate change (2014) impacts, adaptation, and vulnerability part B: regional aspects. Cambridge University Press, Cambridge

Hillbrand A, Borelli S, Conigliaro M, Olivier A (2017) Agroforestry for landscape restoration: exploring the potential of agroforestry to enhance the sustainability and resilience of degraded landscapes. Food and Agriculture Organization of the United Nations, Rome

Hirota M, Holmgren M, Van Nes EH, Scheffer M (2011) Global resilience of tropical forest and savanna to critical transitions. Science 334:232–235

Hoang MH, Namirembe S, van Noordwijk M, Catacutan D, Öborn I, Perez-Teran AS, Nguyen HQ, Dumas-Johansen MK (2014) Farmer portfolios, strategic diversity management and climate-change adaptation–implications for policy in Vietnam and Kenya. Clim Dev 6(3):216–225

Hobbs RJ, Cramer VA (2008) Restoration ecology: interventionist approaches for restoring and maintaining ecosystem function in the face of rapid. Annu Rev Environ Resour 33:39–61. https://doi.org/10.1016/j.cosust.2013.10.013

Huang J, Yu H, Guan X et al (2015) Accelerated dryland expansion under climate change. Nat Clim Chang 6:166–171

Hübner R, Kühnel A, Lu J, Dettmann H, Wang W, Wiesmeier M (2021) Soil carbon sequestration by agroforestry systems in China: a meta-analysis. Agric Ecosyst Environ 315:107437

Hulvey KB, Hobbs RJ, Standish RJ, Lindenmayer DB, Lach L, Perring MP (2013) Benefits of tree mixes in carbon plantings. Nat Clim Chang 3:869–874

ICRAF (2021) Restoring land with agroforestry: new guide published. ICRAF, Bogor

IPBES (2018) Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. Bonn, IPBES Secretariat, p 44

IPCC (2019a) Climate change and land: an IPCC special report on climate change, desertification, land degradation sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva
IPCC (2019b) Summary for policymakers. In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva
IPCC (2021) Summary for policymakers. In: Climate change 2021: the physical science basis. Cambridge University Press, Cambridge
IPCC (Intergovernmental Panel on Climate Change) (2014) Summary for policymakers. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. IPCC, Geneva, p 44
IUCN (2015) Land degradation neutrality: implications and opportunities for conservation. IUCN, Gland
IUCN (2017) The Bonn challenge in Asia: Driving leadership on forest landscape restoration. Forest Brief, no 17. https://www.iucn.org/sites/dev/files/content/documents/20170502_iucn-forest-brief-no-17-bonn-challenge-asia_web.pdf
IUCN (2018) The IUCN red list of threatened species. Retrieved from http://www.iucnredlist.org/. Accessed 22 January 2018
IUCN and WRI (2014) A guide to the restoration opportunities assessment methodology (ROAM): assessing forest landscape restoration opportunities at the national or sub-national level. IUCN, Gland, p 125
Jat ML, Dagar JC, Sapkota TB, Yadvinder-Singh GB, Ridaura SL, Saharawat YS, Sharma RK, Tetarwal JP, Hobbs H, Stirling C (2016) Climate change and agriculture: adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. Adv Agron 137: 1–115
Jha S, Das J, Goyal MK (2019) Assessment of risk and resilience of terrestrial ecosystem productivity under the influence of extreme climatic conditions over India. Sci Rep 9:18923. https://doi.org/10.1038/s41598-019-55067-0
Jones HP, Jones PC, Barbier EB, Blackburn RC, Rey Benayas JM, Holl KD et al (2018) Restoration and repair of Earth's damaged ecosystems. Proc R Soc Lond B Biol Sci 285:20172577. https://doi.org/10.1098/rspb.2017.2577
Jonsson K, Ong CK, Odongo JCW (1999) Influence of scattered nere and karite trees on microclimate, soil fertility and millet yield in Burkina Faso. Exp Agric 35(1):39–53
Jose S, Gold MA, Garrett HE (2012) The future of temperate agroforestry in the United States. In: Nair PKR, Garrity D (eds) Agroforestry - the future of global land use. Advances in agroforestry, vol 9. Springer, Dordrecht, p 245
Kandji ST, Verchot LV, Mackensen J, Boye A, Van Noordwijk M, Tomich CK, Ong CK, Albrecht A, Palm CA (2006) Opportunities for linking climate change adaptation and mitigation through agroforestry systems. In: Garrity DP, Okono A, Grayson M, Parrott S (eds) World agroforestry into the future. World Agroforestry Centre, Nairobi, pp 113–121
Kaur B, Gupta SR, Singh G (2002) Carbon storage and nitrogen cycling in silvi-pastoral systems on a sodic soil in India. Agrofor Syst 54:21–29
Kim DG, Kirschbaum MUF, Beedy TL (2016) Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: synthesizing available data and suggestions for future studies. Agric Ecosyst Environ 226:65–78. https://doi.org/10.1016/j.agee.2016.04.011
Kimaro AA, Timmer VR, Chamshama S, Ngaga Y, Kimaro DA (2009) Competition between maize and pigeonpea in semi-arid Tanzania: effect on yields and nutrition of crops. Agric Ecosyst Environ 134(1-2):115–125
Kimaro AA, Birhane E, Mowo J, Betemariam E, Mpanda M, Hadgn KM (2014) Benefits from the ecosystem services provided by trees-supporting services, soil fertility management. In: De

Leeuw J, Njenga M, Wagner B, Iiyama M (eds) Treesilience: an assessment of the resilience provided by trees in the drylands of Eastern Africa. Nairobi, ICRAF, pp 71–74
Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. For Ecol Manag 246:208–221
Kirui OK, Mirzabaev A (2014) Economics of land degradation in Eastern Africa. University of Bonn, Bonn
Kirui OK, Mirzabaev A, von Braun J (2021) Assessment of land degradation 'on the ground' and from 'above'. SN Appl Sci 3:318. https://doi.org/10.1007/s42452-021-04314-z
Kmoch L, Pagella T, Palm M, Sinclair FL (2018) Using local agroecological knowledge in climate change adaptation: a study of tree-based options in Northern Morocco. Sustain For 10:3719
Kumar BM (2006) Carbon sequestration potential of tropical homegardens. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time-tested example of sustainable agroforestry. Springer, Dordrecht, pp 185–204
Kumar BM, Nair PKR (2004) The enigma of tropical homegardens. Agrofor Syst 61:135–152
Kumar BM, Singh AK, Dhyani S (2012) South Asian agroforestry: traditions, transformations, and prospects. In: Agroforestry: the future of global land use. Springer, Berlin
Kumari C, Gupta SR, Dagar JC, Singh V, Kumar M (2018) Carbon sequestration and microbial biodiversity in agroforestry systems for saline water irrigated semi-arid hyperthermic camborthids regions of north-west India. J Soil Salinity Water Qual 10:133–148
Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. Agron Sustain Dev 39:47. https://doi.org/10.1007/s13593-019-0589-8
Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Kuntashula E, Dimobe K, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes-recent advances and emerging challenges, vol 1. Springer, Singapore, pp 135–167
Labata MM, Aranico EC, Tabaranza ACE, Patricio JHP, Amparado RF Jr (2012) Carbon stock assessment of three elected agroforestry systems in Bukidnon, Philippines. Adv Environ Sci 4(1):5–11
Lal R (2001) Potential of desertification control to sequester carbon and mitigate the greenhouse effect. Clim Chang 51:35–72
Landicho L, Paelmo R, Cabahug R, de Luna C, Visco R, Tolentino L (2016) Climate change adaptation strategies of smallholder agroforestry farmers in the Philippines. J Environ Sci Manag 19(1):37–45
Lasco RD, Pulhin FB (2009) Carbon budgets of forest ecosystems in the Philippines. J Environ Sci Manag 12(1):1–13
Lasco RD, Sales RF, Estrella R, Saplaco SR, Castillo ASA, Cruz RVO, Pulhin FB (2001) Carbon stock assessment of two agroforestry systems in a tropical forest reserve in the Philippines. Philipp Agric Sci 84(4):401–407
Lasco RD, Evangelista RS, Pulhin FB (2010) Potential of community-based forest management to mitigate climate change in the Philippines. Small-scale For 9:429–443
Lin BB (2011) Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61(3):183–193
Lin K, Guo S, Zhang W, Liu P (2007) A new baseflow separation method based on analytical solutions of the Horton infiltration capacity curve. Hydrol Process 21(13):1719–1736
Lin T, Catacutan DC, van Noordwijk M, Finlayson RF, Rogel CN, Orencio P (2021) State and outlook of agroforestry in ASEAN – status, trends and outlook 2030 and beyond. FAO, Bangkok
Liu LP, Long XH, Shao HB, Liu ZP, Tao Y, Zhou QS, Zong JQ (2015) Ameliorants improve saline-alkaline soils on a large scale in northern Jiangsu Province. Ecol Eng 81:328–334
Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agron Sustain Dev 34:443–454. https://doi.org/10.1007/s13593-014-0212-y

Lott JE, Ong CK, Black CR (2009) Understorey microclimate and crop performance in a *Grevillea robusta*-based agroforestry system in semi-arid Kenya. Agric Forest Meteor 149:1140–1151
Mafongoya P, Bation A, Kihara J, Waswa BS (2007) Appropriate technologies to replenish soil fertility in southern Africa. Nutr Cycl Agroecosyst 76(2):29–43
Magaju C, Winowiecki LA, Crossland M, Frija A, Ouerghemmi H, Hagazi N, Sinclair F (2020) Assessing context-specific factors to increase tree survival for scaling ecosystem restoration efforts in East Africa. Landscape 9(12):494. https://doi.org/10.3390/land9120494
Maimunah S, Rahman SA, Samsudin YB, Artati Y, Simamora TI, Andini S, Lee SM, Baral H (2018) Assessment of suitability of tree species for bioenergy production on burned and degraded Peatlands in Central Kalimantan. Land 7:40115. https://doi.org/10.3390/land7040115
Manaye A, Tesfamariam B, Tesfaye M, Worku A, Gufi Y (2021) Tree diversity and carbon stocks in agroforestry systems in northern Ethiopia. Carbon Balance Manag 16:14. https://doi.org/10.1186/s13021-021-00174-7
Mangalassery S, Dayal D, Meena SL, Ram B (2014) Carbon sequestration in agroforestry and pasture systems in arid northwestern India. Curr Sci 107:1200–1293
Mansourian S, Berrahmouni N (2021) Review of forest and landscape restoration in Africa. FAO, Accra
Mansourian S, Parrotta J (2018) Forest landscape restoration: integrated approaches to support effective implementation. Routledge, London, p 249
Martini E, Nguyen HT, Mercado AR Jr, Finlayson RF, Nguyen TQ, Catacutan DC, Triraganon R (2020) Practitioner's field guide: agroforestry for climate resilience. World Agroforestry (ICRAF), Bogor
Masih I, Maskey S, Trambauer P (2014) A review of droughts on the African continent: a geospatial and long-term perspective. Hydrol Earth Syst Sci 18:3635–3649
Mbow C, Smith P, Skole D, Bustamante M, Duguma L (2014a) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr Opin Environ Sustain 6:8–14
Mbow C, van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014b) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67
McNeely J, Schroth G (2006) Agroforestry and biodiversity conservation—traditional practices, present dynamics, and lessons for the future. Biodivers Conserv 15:549–554
Millennium Ecosystem Assessment framework (MEA) (2005) Ecosystems and human well-being. Island Press, Washington
Molua EL (2005) The economics of tropical agroforestry systems: the case of agroforestry farms in Cameroon. Forest Policy Econ 7:199–211
Moreira SLS, Pires CV, Marcatti GE, Santos RHS, Imbuzeiro HMA, Fernandes RBA (2018) Intercropping of coffee with the palm tree, macauba, can mitigate climate change effects. Agric For Meteorol 256–257:379–390
Mulia R, Nguyen MP, Pham TV, Dinh TH (2018) Potential mitigation contribution from agroforestry to Vietnam's NDC. World Agroforestry (ICRAF) Southeast Asia Program, Hanoi
Mulia R, Nguyen DD, Nguyen MP, Steward P, Pham VT, Le HA, Simelton E (2020) Enhancing Vietnam's nationally determined contribution with mitigation targets for agroforestry: a technical and economic estimate. Landscape 9(12):528
Murty D, Kirschbaum MUF, Mcmurtrie ER, Mcgilvray H (2002) Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Glob Chang Biol 8:105–123
Nachtergaele F, Biancalani R, Petri M (2011) Land degradation: SOLAW background thematic report 3. Food and Agriculture Organization of the United Nations (FAO), Rome
Nair PKR (1993) An introduction to agroforestry. Kluwer Academic Publishers, Dordrecht
Nair PKR, Kumar BM, Nair VD (2009a) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23

Nair PKR, Nair VD, Kumar BM, Haile SG (2009b) Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Policy 12:1099–1111

Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Prod 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831

Neumann RB, Cardon ZG (2012) The magnitude of hydraulic redistribution by plant roots: a review and synthesis of empirical and modeling studies. New Phytol 194(2):337–352

Nguyen VX, Park PS, Hoang TMH (2011) Comparison of carbon stock in different agroforestry systems in buffer zone of Ba Be National Park, Vietnam. World Agroforestry Centre (ICRAF), Hanoi

Nguyen Q, Hoang MH, Oborn I, van Noordwijk M (2013) Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. Clim Chang 117(1–2):241–257

Niagi D (2021) Farmers regreen Kenya's drylands with agroforestry and an app. Mongabay series: agroecology, global agroforestry. https://news.mongabay.com/2021/08/farmers-regreen-kenyas-drylands-with-agroforestry-and-an-app/

Niang I, Ruppel OC, Abdrabo MA, Essel A, Lennard C, Padgham J, et al. (2014) Africa. Climate change 2014: impacts, adaptation and vulnerability: part B: regional aspects: working group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change, p. 1199–1266

Niether W, Armengot L, Andres C, Schneider M, Gerold G (2018) Shade trees and tree pruning alter throughfall and microclimate in cocoa (*Theobroma cacao* L.) production systems. Ann For Sci 75:38. https://doi.org/10.1007/s13595-018-0723-9

Nkonya E, Gerber N, von Braun J, de Pinto A (2011) Economics of land degradation: the costs of action versus inaction. IFPRI, Washington DC

Nyamadzawo G, Chikowo R, Nyamugafata P et al (2008) Soil organic carbon dynamics of improved fallow-maize rotation systems under conventional and no-tillage in Central Zimbabwe. Nutr Cycl Agroecosyst 81:85–93

Nzyoka J, Minang PA, Wainaina P, Duguma L, Manda L, Temu E (2021) Landscape governance and sustainable land restoration: evidence from Shinyanga, Tanzania. Sustain For 13(14):7730

Ofori SA, Cobbina SJ, Obiri S (2021) Climate change, land, water, and food security: perspectives from Sub-Saharan Africa. Front Sustain Food Syst 5:680924. https://doi.org/10.3389/fsufs.2021.680924

Olson, L., H. Barbosa, S. Bhadwal, A. Cowie, K. Delusca, D. Flores-Renteria, K. Hermans, E. Jobbagy, W. Kurz, D. Li, D.J. Sonwa, L. Stringer (2019) Land degradation. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Palmer MA, Reidy Liermann CA, Nilsson C, Flörke M, Alcamo J, Lake PS et al (2008) Climate change and the world's river basins: anticipating management options. Front Ecol Environ 6: 81–89

Pendergrast M (2010) Uncommon grounds: the history of coffee and how it transformed our world. Basic Books, New York

Poeplau C, Vos C, Don A (2017) Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soil 3:61–66. https://doi.org/10.5194/soil-3-61-2017

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114: 1571–1596

Priess JA, Mimler M, Klein AM, Schwarze S, Tscharntke T, Steffan-Dewenter I (2007) Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems. Ecol Appl 17:407–417

Quadir M, Oster JD, Schubert S, Noble AD, Sahrawat KL (2007) Phytoremediation of sodic and saline-sodic soils. Adv Agron 96:197–247

Qureshi AS, McCornick PG, Qadir M, Aslam Z (2008) Managing salinity and waterlogging in the Indus Basin of Pakistan. Agric Water Manag 95:1–10

Qureshi AS, Ertebo T, Mehansiwala M (2018) Prospects of alternative copping systems for salt affected soils in Ethiopia. J Soil Sci Environ Manage 9:98–107

Rahman SA, Baral H (2020) Nature-based solution for balancing the food, energy, and environment trilemma: Lessons from Indonesia. In: Dhyani S, Gupta A, Karki M (eds) Nature-based solutions for resilient ecosystems and societies. Springer, Singapore, pp 69–82. https://doi.org/10.1007/978-981-15-4712-6_4

Rahn E, Vaast P, Läderach P, van Asten P, Jassogne L, Ghazoul J (2018) Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol Model 371: 76–89

Ramos HMN, Vasconcelos SS, Kato OR, Castellani DC (2018) Above- and belowground carbon stocks of two organic, agroforestry-based oil palm production systems in eastern Amazonia. Agrofor Syst. https://doi.org/10.1007/s10457-017-0131-4

Reang D, Hazarika A, Sileshi GW, Pandey R, Das AK, Nath AJ (2021) Assessing tree diversity and carbon storage during land use transitioning from shifting cultivation to indigenous agroforestry systems: implications for REDD+ initiatives. J Environ Manag 298:113470. https://doi.org/10.1016/j.jenvman.2021.113470

Reij C, Tappan G, Smale M (2009) Re-greening the Sahel: farmer-led innovation in Burkina Faso and Niger. In: Spielman D, Pandya-Lorch R (eds) Millions Fed. Proven successes in agricultural development. IFPRI, Washington, pp 53–58

Rey Benayas JM, Bullock JM (2012) Restoration of biodiversity and ecosystem services on agricultural land. Ecosystems 15:883–899

Rey Benayas JM, Newton AC, Diaz A, Bullock JM (2009) Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325:1121–1124

Ricketts KD, Turvey CG, Gómez MI (2014) Value chain approaches to development: smallholder farmer perceptions of risk and benefits across three cocoa chains in Ghana. J Agribus Dev Emerg Econ 4:2–22

Ringler C, Zhu T, Cai X, Koo J, Wang D (2010) Climate change impacts on food security in sub-Saharan Africa: insights from comprehensive climate change scenarios (No. 1042). International Food Policy Research Institute (IFPRI), Washington

Rosenstock TS, Dawson IK, Aynekulu E, Chomba S, Degrande A, Fornace K, Jamnadass R, Kimaro A, Kindt R, Lamanna C et al (2019) A planetary health perspective on agroforestry in Sub-Saharan Africa. One Earth 1:330–344. https://doi.org/10.1016/j.oneear.2019.10.017

Roshetko M, Delaney M, Hairiah K, Purnomosidhi P (2002) Carbon stocks in Indonesian homegarden systems: can smallholder systems be targeted for increased carbon storage? Am J Altern Agric 17:125–137

Safriel U (2014) The water regulation service of dryland agroforestry ecosystems. In: De Leeuw J, Njenga M, Wagner B, Iiyama M (eds) Treesilience: an assessment of the resilience provided by trees in the drylands of Eastern Africa. ICRAF, Nairobi, pp 87–92

Samain O, Kergoat L, Hiernaux P, Guichard F, Eric M, Franck T, Lavenu F (2008) Analysis of the in situ and MODIS albedo variability at multiple time scales in the Sahel. J Geophys Res 113: 14119

Samsudin YB, Puspitaloka D, Rahman SA, Chandran A, Baral H (2020) Community-based peat swamp restoration through agroforestry in Indonesia. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore

Santhyami S, Basukriadi A, Patria M, Abdulhadi R (2018) The comparison of aboveground C-stock between cacao-based agroforestry system and cacao monoculture practice in West Sumatra, Indonesia. Biodiversitas 19:472–479

Santos PZF, Crouzeilles R, Sansevero JBB (2019) Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. For Ecol Manag 433:140–145

Scharlemann JP, Edmund W, Tanner VJ, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manage 5(1):81–91. https://doi.org/10.4155/cmt.13.77
Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: Linking theory to observation. Trends Ecol Evol 18:648–656
Schoeneberger MM, Bentrup G, Gooijer de H, Soolanayakamahally R, Sauer T, Brandle J, Zhou X, Current D (2012) Branching out: agroforestry as a climate change mitigation and adaptation for agriculture. J Soil Water Conserv 67:128–136
SER (2004) International Primer on ecological restoration science & policy working group (version 2). Society for Ecological Restoration, Washington
Sharma A, Goyal MK (2017) Assessment of ecosystem resilience to hydroclimatic disturbances in India. Glob Chang Biol 2:2017
Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agrofor Syst 60:123–130
Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad Dev 29:3886–3897. https://doi.org/10.1002/ldr.3136
Siarudin M, Rahman SA, Artati Y, Indrajaya Y, Narulita S, Ardha MJ, Larjavaara M (2021) Carbon sequestration potential of agroforestry systems in degraded landscapes in West Java, Indonesia. Forests 12:714
Sileshi GW, Akinnifesi FK, Ajayi OC, Muys B (2011) Integration of legume trees in maize-based cropping systems improves rainfall use efficiency and crop yield stability. Agric Water Manag 98:1364–1372
Sileshi GW, Mafongoya PL, Akinnifesi FK, Phiri E, Chirwa P, Beedy T, Makumba W, Nyamadzawo G, Njoloma J, Wuta M, Nyamugafata P, Jiri O (2014) Fertilizer trees. Encyclopedia of agriculture and food systems, vol 1. Elsevier, San Diego, pp 222–234
Sileshi GW, Teketay D, Gebrekirstos A, Hadgu K (2020) Sustainability of *Faidherbia albida*-based agroforestry in crop production and maintaining soil health. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 2. Springer, Singapore, pp 349–369
Sileshi GW, Dagar JC, Nath AJ, Teketay D (2022) Agroforestry as a climate-smart agriculture: strategic interventions, current practices and policies. In: Dagar JC, Gupta SR, Sileshi GW (eds) Agroforestry for degraded landscapes. Springer, Singapore
Sinclair FL, Wezel A, Mbow C, Robiglio V, Harrison R, Chomba C (2019) The contribution of agroecological approaches to realizing climate-resilient agriculture. Background Paper Global Commission on Adaptation Rotterdam
Singh G, Dagar JC (2005) Greening sodic lands: Bichhian model. Technical Bulletin No.2/2005. Central Soil Salinity Research Institute, Karnal, p 51
Singh M, Arrawatia ML, Tewari VP (1998) Agroforestry for sustainable development in arid zones of Rajasthan. Int Tree Crops J 9:203–212
Singh VP, Sinha RB, Nayak D, Neufeldt H, van Noordwijk M, Rizvi J (2016) The national agroforestry policy of India: experiential learning in development and delivery phases. ICRAF Working Paper No. 240. World Agroforestry Centre, New Delhi. https://doi.org/10.5716/WP16143.PDF
Singh K, Singh RP, Tewari SK (2021) Ecosystem restoration: challenges and opportunities for India. Restor Ecol 29(3):13341. https://doi.org/10.1111/rec.13341
Smith DM (2008) Determination of plant water sources using stable isotopes: a strategic tool for planning water resource management for agroforestry. In: Management of agroforestry systems for enhancing resource use efficiency and crop productivity. Food and Agriculture Organization & International Atomic Energy Agency (IAEA), Vienna, pp 29–42
Smithson PC, Giller KE (2002) Appropriate farm management practices for alleviating N and P deficiencies in low-nutrient soils of the tropics. Plant Soil 245(1):169–180

Solh M (2009) Keynote presentation 2: The role of science and technology in combating desertification, land degradation and drought in the dry areas. O¢ce for O¢cial Publications of the European Communities, Luxembourg, pp 12–16
Soni ML, Subbulakshmi V, Yadava ND, Dagar JC (2017) Agroforestry for increasing farm productivity in water-stressed ecologies. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 369–411
Strassburg BBN, Iribarrem A, Beyer HL, Cordeiro CL, Crouzeilles R, Jakovac CC, Visconti P (2020) Global priority areas for ecosystem restoration. Nature 586(7831):724–729. https://doi.org/10.1038/s41586-020-2784-9
Sutton PC, Anderson SJ, Costanza R, Kubiszewski I (2016) The ecological economics of land degradation: impacts on ecosystem service values. Ecol Econ 129:182–192. https://doi.org/10.1016/j.ecolecon.2016.06.016
Tewari JC, Ram M, Roy MM, Dagar JC (2014) Livelihood improvements and climate change adaptations through agroforestry in hot arid environments. Agroforestry systems in India: livelihood security & ecosystem services. Springer, New Delhi, pp 155–184
Thompson HE, Berrang-Ford L, Ford JD (2010) Climate change and food security in Sub-Saharan Africa: a systematic literature review. Sustain For 2:2719–2733. https://doi.org/10.3390/su208271
Timpane-Padgham BL, Beechie T, Klinger T (2017) A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLoS ONE 12(3): e0173812. https://doi.org/10.1371/journal.pone.0173812
Tolentino L, Landicho L, Cabahug R, de Luna C (2010) Case study: agroforestry in the Philippines. In: Lever-Tracy C (ed) Handbook on climate change and society. Routledge, Milton Park
Udawatta RP, Gantzer CJ, Jose S (2017) Agroforestry practices and soil ecosystem services. In: Al-Kaisi MM, Lowery B (eds) Soil health and intensification of agroecosytems. Academic Press, London, pp 305–333
UNCCD (2017a) Global land outlook. UNCCD, Bonn
UNCCD (2017b) Global land outlook, 1st edn. UNCCD, Bonn
United Nations Environment Programme (UNEP) (2021) Becoming#GenerationRestoration: ecosystem restoration for people, nature and climate. UNEP, Nairobi
Vaast P, Somarriba E (2014) Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agrofor Syst 88:947–956
Valderrábano M, Nelson C, Nicholson E, Etter A, Carwardine J, Hallett JG, McBreen J, Botts E (2021) Using ecosystem risk assessment science in ecosystem restoration: a guide to applying the Red List of Ecosystems to ecosystem restoration. IUCN, Gland
van Noordwijk M (2019) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor
van Noordwijk M, Hoang M, Neufeldt H, Oborn I, Yatich T (eds) (2011) How trees and people can co-adapt to climate change reducing vulnerability in multifunctional landscapes. Nairobi, World Agroforestry Centre (ICRAF), p 136
van Noordwijk M, Duguma LA, Dewi S, Leimona B, Catacutan DC, Lusiana B, Öborn I, Hairiah K, Minang PA (2018) SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? Curr Opin Environ Sustain 34:33–42. https://doi.org/10.1016/j.cosust.2018.09.003
van Noordwijk M, Rahayu S, Gebrekirstos A, Kindt R, Tata HL, Muchugi A, Ordonez JC, Xu J (2019a) Tree diversity as basis of agroforestry. In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor, pp 17–44
van Noordwijk M, Bargues-Tobella A, Muthuri CW, Gebrekirstos A, Maimbo M, Leimona B, Bayala J, Ma X, Lasco R, Xu J, Ong CK (2019b) Agroforestry as part of nature-based water management. In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor, pp 305–333

van Noordwijk M, Duguma LA, Dewi S, Leimona B, Catacutan D, Lusiana B, Oborn I, Hairiah K et al (2019c) Agroforestry into its fifth decade: local responses to global challenges and goals in the Anthropocene. In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor, pp 405–428

van Noordwijk M, Coe R, Sinclair FL, Luedeling E, Bayala J, Muthuri CW, Cooper P, Kindt R, Duguma L, Lamanna C, Minang PA (2021) Climate change adaptation in and through agroforestry: four decades of research initiated by Peter Huxley. Mitig Adapt Strateg Glob Chang 26: 18. https://doi.org/10.1007/s11027-021-09954-5

Vandenbeldt RJ, Williams JH (1992) The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. Agric For Meteorol 60:93–100

Vargas R, Pankova EI, Balyuk SA, Krasilnikov PV, Khasankhanova GM (2018) Handbook for saline soil management. Food and Agriculture Organization of the United Nations and Lomonosov Moscow State University, Rome

Verdone M, Seidl A (2017) Time, space, place, and the Bonn challenge global forest restoration target. Restor Ecol 25:903–911

Wainaina P, Minang PA, Nzyoka J, Duguma L, Temu E, Manda L (2021) Incentives for landscape restoration: lessons from Shinyanga, Tanzania. J Environ Manag 280:111831

Waldron A, Garrity D, Malhi Y, Girardin C, Miller DC, Seddon N (2017) Agroforestry can enhance food security while meeting other sustainable development goals. Trop Conserv Sci 10: 194008291772066

Walker B, Salt D (2012) Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social—ecological systems. Ecol Soc 9(2):5

Wardah, Toknok B, Zulkhaidah (2011) Carbon stock of agroforestry systems at adjacent buffer zone of Lore Lindu National Park, Central Sulawesi. J Trop Soil 16(2):123–128

Webb NP et al (2017) Land degradation and climate change: building climate resilience in agriculture. Front Ecol Environ 15:450–459. https://doi.org/10.1002/fee.1530

Wei X, Shao M, Gale W, Li L (2015) Global pattern of soil carbon losses due to the conversion of forests to agricultural land. Sci Rep 4:4062. https://doi.org/10.1038/srep04062

Williams SE, Shoo LP, Isaac JL, Hoffmann AA, Langham G (2008) Towards an integrated framework for assessing the vulnerability of species to climate change. PLoS Biol 6(12):e325

Williamson RB, Smith CM, Cooper AB (1996) Watershed riparian management and its benefits to a eutrophic lake. J Water Resour Plan Manag 122(1):24–32

Wilson J, Ndufia J (2014) Benefits from the ecosystem services provided by trees-supporting services, soil moisture. In: De Leeuw J, Njenga M, Wagner B, Iiyama M (eds) Treesilience: an assessment of the resilience provided by trees in the drylands of Eastern Africa. Nairobi, ICRAF, pp 74–78

World Bank (2004) Sustaining forest: a development strategy. World Bank, Washington

WRI (2008) Roots of resilience—growing the wealth of the poor. World Resources Institute, Washington

WRI India (2020) Restoring landscapes in India for climate and communities: key findings from Madhya Pradesh's Sidha district. World Resources Institute, Bengaluru

Xu B, Yang Y, Li P, Shen H, Fang J (2014) Global patterns of ecosystem carbon flux in forests: a biometric data-based synthesis. Glob Biogeochem Cycles 28:962–973

Yadav GS, Kandpal BK, Das A, Babu S et al (2021) Impact of 28 year old agroforestry systems on soil carbon dynamics in Eastern Himalayas. J Environ Manag 283:111978. https://doi.org/10.1016/j.jenvman.2021.111978

Yamba B, Larwanou M, Hassane A, Reij C (2005) Niger study: Sahel pilot study report. U.-S. Agency for International Development and International Resources Group, Washington

Young A (1997) Agroforestry for soil management, 2nd edn. CAB International, Wallingford

Zewdie A (2014) Impacts of climate change on food security: a literature review in Sub Saharan Africa earth science and climatic change. J Earth Sci Clim Change 5:8–11. https://doi.org/10.4172/2157-7617.1000225

Zhang SJ (2010) Crop production on acid soils: Overcoming aluminium toxicity and phosphorus deficiency. Ann Bot 106(1):183–184

Zomer RJ, Trabucco A, Coe R, Place F (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. In: ICRAF (ed) Working paper no. 89. World Agroforestry Centre, Nairobi, p 72

Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. Working Paper 179. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Bogor

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, Van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6:29987

Chapter 6
The Great Green Wall Initiatives and Opportunities for Integration of Dryland Agroforestry to Mitigate Desertification

Gudeta Weldesemayat Sileshi, Jagdish Chander Dagar, Shem Kuyah, and Ashim Datta

Abstract Drylands are vulnerable to climate change and land degradation, and increasing aridity is projected to affect their structural and functional attributes. Approximately 70% of the dryland areas are located in Africa and Asia. Human-induced land degradation is a driver of desertification, wind erosion and a major contributor of sand and dust storms. The objectives of this chapter are to provide a synthesis of: (1) trends in aridity, desertification and their impacts on human health and the environment; (2) the evidence for mitigation of desertification drawing parallels between Africa and Asia in implementation of Green Wall initiatives; and (3) the opportunities and challenges for integrating agroforestry for mitigation of desertification in the drylands of Africa and Asia. The literature reviewed provides substantial evidence that desert dust plays an important role in different aspects of weather, climate and atmospheric chemistry, and represents a severe hazard to human and the environmental health. The African continent is the most important source of desert dust, with over 50% of the atmospheric dust originating in the Sahara. Sand storms and dune movement pose a serious threat to irrigated farmlands, villages, road and transport infrastructure as well as solar and wind energy harvesting facilities. Not only people living in dry lands but also populations far

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from these regions can be exposed to a wide range of air quality-related health problems arising from desert dust. Epidemiological studies and meta-analyses provide substantive evidence for severe health hazards, hospitalizations and mortality due to exposure to desert dust even in areas thousands of kilometres away from the source. This calls for treating desertification in drylands as a global environmental and human health imperative and the need for greater investment in mitigation measures such as agroforestry. Such investments should be pursued not only from national governments but also from local governments of distant megacities that are affected by desert dust annually. The wider adoption of agroforestry may not only solve local land degradation problems but it can also help in tackling global health and environmental challenges caused by desertification. Here, we provide the opportunities and challenges for integrating agroforestry in on-going Green Wall initiatives.

Keywords Dust storms · Desertification · Health hazards · Megacities · The Great Green Wall

6.1 Introduction

Drylands currently cover 42–46% of the global land area (Table 6.1), where over three billion people or ~38% of the total global population lives (Mirzabaev et al. 2019; Koutroulis 2019; Prăvălie 2016; van der Esch et al. 2017). The highest number of people live in the drylands of South Asia, followed by Sub-Saharan Africa and Latin America (van der Esch et al. 2017). The drylands in these continents are especially threatened by desertification, drought, dust storms, heat waves, water stress, extreme rainfall events, wildfire and disease emergence (Prăvălie 2016). Drylands are especially vulnerable to climate change, land degradation and desertification (Berdugo et al. 2020; Huang et al. 2016). Increasing aridity is the hallmark of climate change in drylands, and it is projected to affect multiple structural and functional attributes of the ecosystems (Berdugo et al. 2020; Huang et al. 2016). Climate variability and anthropogenic climate change, particularly through increases in land surface air temperature and evapotranspiration, and decreases in precipitation play a role in causing desertification in some drylands (Mirzabaev et al. 2019). The

Table 6.1 Extent of dry lands (area in million km^2) according to different estimates

	Maps		
Dryland type	UNEP-WCMC	CGIAR-CSI	USGS-ESRI
Hyperarid	9.8	11.0	
Arid	15.7	18.0	11.6
Semiarid	22.7	24.2	
Dry subhumid	13.1	13.2	53.9
Total	61.2	66.4	65.5
Share (%) of global land area	41.7	45.3	44.6

major human drivers of desertification are expansion of croplands, unsustainable land management practices and increased pressure on land, which also interact with climate change (Mirzabaev et al. 2019).

Land degradation and desertification pose serious threats to the environment and livelihoods of populations inhabiting drylands (World Bank 2019). Locally, shifting sand is one of the major problems of desertification and land degradation in arid and semiarid areas. Sand storms and dune movement pose a serious threat to irrigated farmlands, villages, railways, highways and wind and solar energy infrastructures (Mirzabaev et al. 2019; Veste et al. 2006). Desertification in one area can also have significant impacts not only in areas close to the source points but over areas thousands of kilometres away because dust can be transported over long distances. For example, dust from the Sahara Desert has been reported to affect air quality and human health in areas as far as North America, the Caribbean and Europe (Creamean et al. 2013; de Longueville et al. 2013; Griffin et al. 2001; Hashizume et al. 2020; Qor-el-aine et al. 2022; Tobias and Stafoggia 2020; Zhang et al. 2016). Similarly, dust from Central Asia and China can affect the European Alps, South Korea, Japan, the Pacific Islands and North America (World Bank 2019).

Populations residing in dryland are highly vulnerable to the impacts of desertification (Lawrence et al. 2018) because of their dependence on agricultural and agropastoral livelihoods, which are the most susceptible to climate change (Mirzabaev et al. 2019; Rosenzweig et al. 2014). The highest numbers of people affected by desertification are in South and East Asia, the circum-Sahara region including North Africa and the Middle East (Mirzabaev et al. 2016, 2019). There is an increasing concentration of poverty in the dryland areas of sub-Saharan Africa and South Asia, where 41% and 12% of the total populations live in extreme poverty, respectively (World Bank 2018). Among the most vulnerable populations are pastoral and agropastoral households (Mirzabaev et al. 2019).

During the last couple of decades, national governments and international organizations have taken many initiatives to control desertification and improve the environment. One of the most notable efforts has been the large-scale afforestation projects such as the great green wall initiatives in China (Parungo et al. 1994; Wang et al. 2010) and Africa (O'Connor and Ford 2014), and similar initiatives in South America and Australia (Maestre et al. 2012). The Green Wall initiative has been implemented as a means of reducing the impacts of desertification in China since the 1970s (Parungo et al. 1994). The concept was similarly applied to counter desertification in the Sahel through the planting of a continuous band of trees from Senegal to Djibouti (O'Connor and Ford 2014). However, the impacts of these programmes have been a subject of intense debate and scientific scrutiny (Jiang 2016; Mitchell et al. 1998; Mirzabaev et al. 2021, 2022; O'Connor and Ford 2014; Parungo et al. 1994; World Bank 2019). The Green Wall concept has received renewed impetus in the light of accelerated desertification associated with climate change (O'Connor and Ford 2014). Such initiatives are increasingly being considered as part of many national and international policies and actions to combat desertification (Benhizia et al. 2021; Goffner et al. 2019; Mirzabaev et al. 2022; UNCCD 2019).

Most of these initiatives focus on establishment of shelterbelts (Veste et al. 2006; World Bank 2019), but investment in sustainable land management has been very limited. A growing body of evidence suggests that sustainable land management practices including agroforestry, improved rangeland management, reduced tillage, crop diversification, judicious irrigation, maintaining permanent soil cover with crop residues can reduce or even reverse desertification (Mirzabaev et al. 2019). For a long time, the role of agroforestry in combating desertification has been recognized (Sileshi et al. 2007), and it has become one of the activities of the thematic programme network in Asia, Africa and Latin America established in the framework of the UNCCD (UNCCD 2007). The World Bank (2019) and UNCCD (Sanz et al. 2017) reports identify agroforestry as one of the effective measures against wind erosion and decreasing dust transport. However, implementation of agroforestry is often unsatisfactory even in large initiatives such as Green Walls. Evidence-based practices and policy are urgently needed to increase implementation of agroforestry. A key challenge has been the inability to match and deploy agroforestry solutions to tackle land degradation and climate change. Land degradation can occur anywhere, but when it occurs in drylands, it is considered desertification. Until recently, desertification has been a highly debated concept, where many scientific studies have downplayed its extent, rate of change and importance (Sterk and Stoorvogel 2020). Its definition has also evolved over the years. Therefore, the objectives of this chapter are to provide a synthesis of: (1) trends in aridity, desertification and their impacts on human health and the environment; (2) the evidence for mitigation of desertification drawing parallels between Africa and Asia in implementation of Green Wall initiatives; and (3) the opportunities and challenges for integrating agroforestry for mitigation of desertification in the drylands of Africa and Asia. We conducted a comprehensive literature review collating information from official reports, individual studies as well as systematic reviews and meta-analyses to build the evidence.

6.2 Drylands, Desertification and their Impacts

6.2.1 Nature and Extent of Drylands and Trends in Aridity

Drylands are often defined and classified based on the aridity index (AI), which is calculated as the ratio of average annual precipitation to potential evapotranspiration (Huang et al. 2016). Accordingly, drylands are defined as regions with AI < 0.65, which are further divided into subtypes as hyperarid (AI < 0.05), arid (0.05–0.20), semiarid (0.20–0.50) and dry subhumid (0.50–0.65) regions (Cherlet et al. 2018; Huang et al. 2016; Prăvălie 2016). Each of these subtypes can occur in different climate zones including tropical, sub-tropical, temperate or polar climates (Fig. 6.1). However, the classification of drylands is still incomplete due to the various on-going discussions (see Fig. 6.1). In addition, AI is not an accurate proxy for delineating drylands in an increasing CO_2 environment (see Mirzabaev et al. 2019).

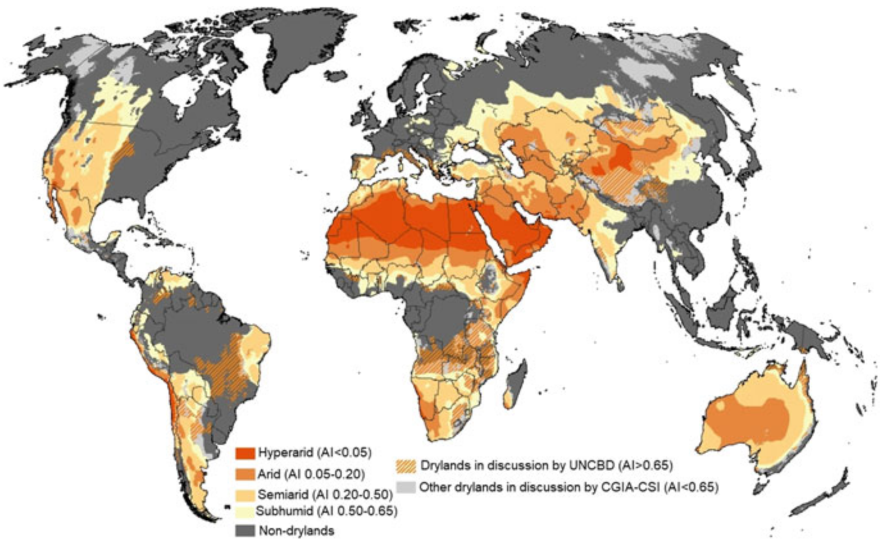

Fig. 6.1 Global distribution of drylands and the different subtypes (adapted from FAO and ITPS 2021)

The estimated total area of drylands and the area under each subtype may vary depending on the concepts and objectives of the organizations in charge of the classification as well as the mapping assumptions and precision of the aridity index (Table 6.1). For example, the United Nations Convention to Combat Desertification (UNCCD) excludes hyperarid zones with the assumption that they are not prone to desertification (Zdruli et al. 2010). On the other hand, the United Nations Convention on Biological Diversity (UNCBD) considers not only hyperarid ecosystems but also humid areas (AI > 0.65) that are functionally connected and that in some cases are difficult to separate from drylands (Sörensen 2007). The map produced by the UNEP-World Conservation Monitoring Centre (UNEP-WCMC) (Sörensen (2007) yields a total dryland area of 61.2 million km^2. A second map, produced by the CGIAR Consortium for Spatial Information (CGIAR-CSI) (Trabucco and Zomer 2019) based on the third edition of the World Atlas of Desertification, yields a total dryland area of 66.4 million km^2. A third map produced as part of the World Terrestrial Ecosystems platform, Nature Conservancy and USGS USGS-ESRI (Sayre et al. 2020) yield a total area of 65.5 million km^2 (Table 6.1). Accordingly, the area of drylands as a percentage of the total global land area of 146.7 million km^2 is 41.7%, 45.3% and 44.6% based on the UNEP-WCMC, CGIAR-CSI and USGS-ESRI aridity maps, respectively. The USGS-ESRI uses only two main intervals of the aridity index. Evidently, these differences result in large discrepancies in estimates.

Each of the dryland subtypes is affected by degradation processes differently. Land degradation processes may take the form of vegetation degradation, water and wind erosion, loss of soil organic carbon and nutrients, soil compaction and

Table 6.2 Tree cover change (in %), area of dryland affected by fire (in %), water stress (in %), loss of fertility (in %) and strong erosion (in million ha). Strong erosion is defined as >10 Mg ha^{-1} $year^{-1}$ degradation factors (adapted from FAO and ITPS 2021)

Dryland type	Tree cover change (2000–2019)	Fire (2018–2019)	Water stress	Loss of fertility	Strong erosion
Hyperarid	0	1.1	44.8	2.2	6.1
Arid	0.1	6.0	29.1	19.2	25.7
Semiarid	1.2	20.1	34.6	23.1	65.0
Dry subhumid	3.3	32.9	23.0	18.4	66.1

salinization in drylands (Prăvălie 2016). For example, the area affected by tree cover change and fire is higher in dry subhumid areas than the other drylands, while the area affected by water stress is higher in hyperarid areas. On the other hand, the area affected by loss of fertility is higher in semiarid areas (Table 6.2). Note that semiarid and dry subhumid areas are characterized by sedentary agriculture. In those areas, crop management and practices that result in poor vegetation growth and low soil cover increase risks of wind erosion. In addition, land management practices that result in deforestation and clearance of vegetation will lead to an increase in wind velocity, and consequently wind erosion. This and the greater intensity and frequency of fires, higher deforestation and erosion rates in dry subhumid areas (Table 6.2) emphasizes the point that desertification can take a greater toll on the land in subhumid drylands.

6.2.2 Desertification Trends and Extent

Following the most recent IPCC circumscription (Mirzabaev et al. 2019), desertification is strictly defined here as land degradation in arid, semi-arid, and dry sub-humid areas. For clarity, land degradation is defined as long-term reduction or loss of biological productivity, ecological integrity or value to humans (IPCC 2019). Desertification is not limited to irreversible forms of land degradation (Sterk and Stoorvogel 2020), nor is it equivalent to desert expansion, but it represents all forms and levels of land degradation occurring in drylands (Mirzabaev et al. 2019). Desertification is a result of complex interactions within coupled social-ecological systems (Mirzabaev et al. 2019). The emerging consensus is that the relative roles of climatic and anthropogenic factors on desertification are location-specific and evolve over time. The high natural climate variability in dryland regions is a major cause of vegetation changes but that does not necessarily imply degradation. However, if droughts increase in frequency, intensity and/or duration, it may overwhelm the vegetation's ability to recover (Mirzabaev et al. 2019). The AR5 Working Group II identified desertification as a process that can lead to reductions in crop productivity and the resilience of agricultural and pastoral livelihoods (Field et al. 2014). Climate change will amplify water scarcity, with negative impacts on agricultural systems, particularly in semi-arid environments of Africa, while droughts could exacerbate desertification in south-western parts of Central Asia (Field et al. 2014). The World Atlas of Desertification (Cherlet et al. 2018) provides up-to-date information on the extent of desertification.

Africa and Asia have the most extensive dryland systems on earth (Prăvălie 2016). Approximately 70% of dryland areas are located in Africa and Asia (Mirzabaev et al. 2019). In Africa, 46 of the 54 countries are affected by aridity and vulnerability to desertification (Prăvălie 2016). Over recent decades, moderate or higher severity degradation has been identified in many river basins including the Nile, Niger, Senegal, Volta and Limpopo (Mirzabaev et al. 2019). The Sahel, the Horn of Africa and southern Africa are the regions most affected (Mirzabaev et al. 2019). Desertification in the Sahel has been a major concern since the 1970s, while it has also been one of the most contested in the scientific literature (Sterk and Stoorvogel 2020). Nevertheless, empirical evidence is increasing on the extent and impacts of desertification in Africa (see details in Mirzabaev et al. 2019). For example, the Sahara expanded by 10% over the twentieth century (Thomas and Nigam 2018), and by 8% between 1950 and 2015 (Liu and Xue 2020). Currently, the African continent is the most important source of desert dust, with over 50% of the atmospheric dust originating in the Sahara (Middleton 2017). The extreme Saharan dust event that occurred on 14–19 June 2020 was the most intensive dust storm in the last 50 years (Qor-el-aine et al. 2022).

In Asia, 38 countries are affected by drylands and prone to desertification (Prăvălie 2016). The Indo-Gangetic Basin in India, Indus Basin in Pakistan, Yellow River Basin and Yinchuan Plain in China, Aral Sea Basin of Central Asia are undergoing salinization (Mirzabaev et al. 2019). China is one of the countries most affected with vast areas of desertification. China has been battling large-scale desertification since the 1950s (Zheng et al. 2006). The main centres of desertification are Xinjiang, Inner Mongolia, Tibet, Gansu, Qinhai, Shannxi, Ningxia and Hebei province (Veste et al. 2006). The desertification belt is located in the arid and semi-arid zone of China covering approximately 3.32 million km^2, of which 2.62 million km^2 (79%) has been desertified (Li et al. 2007).

Drylands are vulnerable to climate change (Berdugo et al. 2020), and there is high confidence that the risks of desertification will increase due to climate change (Mirzabaev et al. 2019). This may lead to large increases in potential evapotranspiration and decrease in precipitation, and consequently decreases in aridity index in some drylands and increase in hyperarid areas (Zhao and Dai 2015). As such, there is high confidence that aridity will increase in some places (Mirzabaev et al. 2019). The IPCC Special Report on Global Warming (Hoegh-Guldberg et al. 2018a, b) concluded that warming by 1.5 °C will considerably increase the risk of aridity for the Southern Africa region. The analysis of global and regional climate models concludes that under all representative concentration pathways, potential evapotranspiration would increase worldwide as a consequence of increasing surface temperatures and surface water vapour deficit (Sherwood and Fu 2014).

Using historical data, Huang et al. (2016) showed an increase in dryland expansion rates resulting in the drylands covering half of the global land surface by the end of this century. Relative to the 1961–1990 baseline, dryland areas projected under RCP8.5 and RCP4.5 will increase by 23% and 11%, respectively (Huang et al. 2016). The increasing aridity, enhanced warming and rapidly growing human population will exacerbate the risk of land degradation and desertification especially in developing countries, where 78% of dryland expansion and 50% of the population growth will occur under RCP8.5 (Huang et al. 2016). Drylands are also predicted to become warmer with an increasing frequency of extreme drought and high rainfall events (Donat et al. 2016). Projected anthropogenic warming is expected to double the risk of concurrent hot and dry extremes. This simultaneous occurrence of extremes across multiple regions is referred to as spatially compound extremes (Singh et al. 2022). Recent analyses show that El Nino conditions lead to the intense and widespread drying over Central America, Amazon, West Africa, East Africa, East Asia, South Asia and Southeast Asia in the historical climate (Singh et al. 2022). Around 80% of historical compound droughts over tropical/subtropical belt are associated with El Nino conditions during the boreal summer (Singh et al. 2022). There is substantial evidence that climate change has already increased drought risk and severity in some regions (Cook et al. 2020). Relative to the late-twentieth century, the probability and severity of compound droughts is projected to increase by ~60% and 20%, respectively, by the late-twenty-first century (Singh et al. 2022).

Recent analyses by Berdugo et al. (2020) demonstrate that aridification will result in systemic and abrupt changes in multiple ecosystem attributes. Berdugo et al. (2020) provide a map of climate change vulnerability in global drylands including areas that will cross each of the thresholds by 2100 under the IPCC assumption of sustained increase in CO_2 emissions in representative concentration pathways (i.e. RCP8.5 scenario).

6.2.3 *Impacts of Desertification*

Desertification leads to conditions that favour the production of dust storms (Mirzabaev et al. 2019). With the expansion of dry lands and attendant desertification, humans and their environment are likely to face increasing risks of frequent exposure to dust and sand storms in the drylands themselves and distant urban centres and megacities. The dust storms are seasonal as indicated in Fig. 6.2b. Asian dust is a seasonal meteorological phenomenon caused by dust storms that originate in the deserts of Mongolia and northern China and are carried eastward along mid-latitude westerlies to pass over China, Korea, and Japan (Hashizume et al. 2020). Sand and dust storms from the Gobi Desert return periodically in winter and spring (Veste et al. 2006). Since the 1950s a drastic increase in the occurrence of dust storms has been observed. As the dust travels thousands of kilometres, it absorbs airborne pollutants from industrial areas (Mori et al. 2003; Takemura et al. 2002). The coarse particles of desert dust are considered potentially toxic, and their

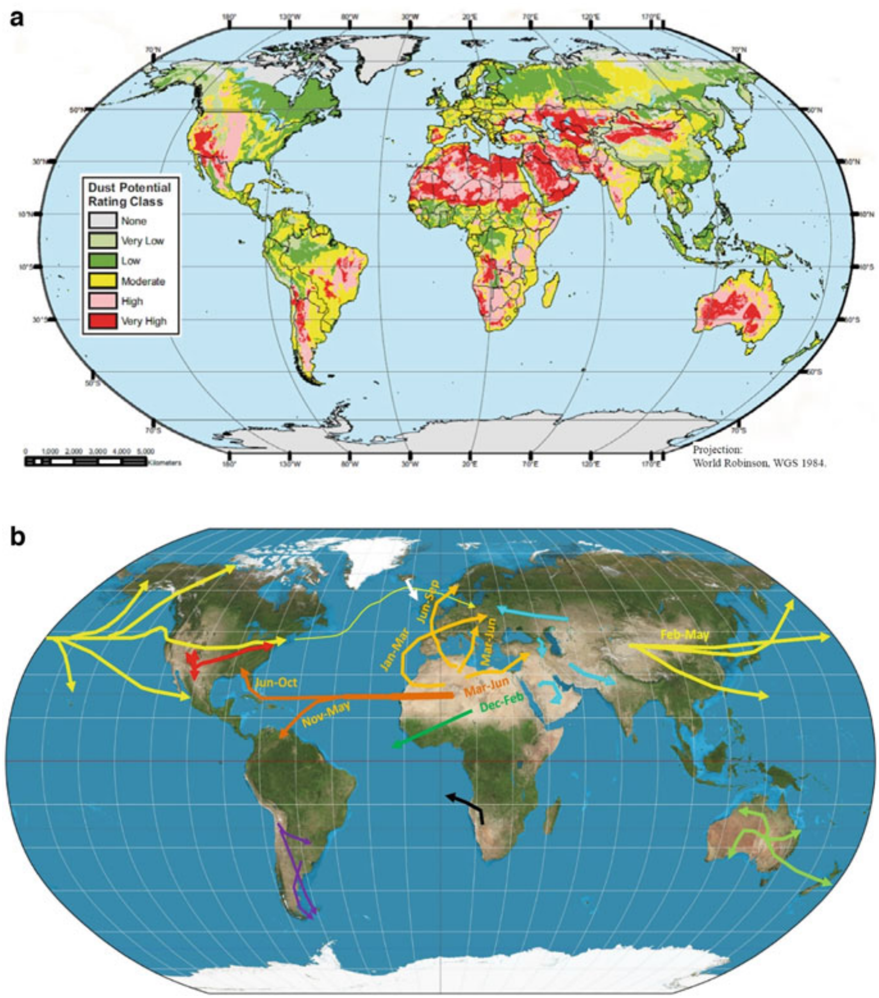

Fig. 6.2 Sources of dust (**a**) and seasonality and direction of dust movement (**b**). Source: Goudie (2014)

constituents vary during long-range transport (Mori et al. 2003). During storm periods, significant amounts of suspended sand and dust may provide a platform to intermix with industrial pollutants (Ho et al. 2019; Rodríguez et al. 2011) that may increase the bioreactivity of dust particles.

Historically, dust storms have impacted air quality and human health in cities like Athens, Beijing, Brisbane, Dubai, Jaipur, Jedda, Kano, Madrid, Melbourne, Phoenix, Seoul, Shanghai, Sydney, Taipei, Tehran and Tokyo (Goudie 2014). The main sources of desert dust are the Sahara, central and eastern Asia, the Middle East, and parts of the western USA (Fig. 6.2a; Goudie 2014). Desert dust may carry various pollutants including heavy metals and pesticides, as well as biological materials such as fungi and bacteria (Rodríguez et al. 2011). Past studies (e.g. De Longueville et al. 2010; Fussell and Kelly 2021; Goudie 2014; Mahowald et al. 2010; Tobias and Stafoggia 2020; Zhang et al. 2016) have shown that desert dust plays an important role in different aspects of weather, climate, atmospheric chemistry, geochemistry and represents a severe hazard to environment and health. In certain parts of the world, the frequency and scale of dust storms have increased in response to land use and climatic changes (Goudie 2014). With climate change compounding on-going development challenges, significant economic and humanitarian costs are projected (Speranza and Scholz 2013). The literature shows that desertification impacts humans and their environment in different ways, ranging from impact on health to ecosystems and infrastructure. These are briefly reviewed below.

6.2.3.1 Impact on Human Health

One of the major threats arising from desertification is the health impacts of dust storms. The health impacts of dust storms are largest in areas in the immediate vicinity of their origin, primarily the Sahara Desert, followed by Central and eastern Asia, the Middle East and Australia (Mirzabaev et al. 2019). Desert dust outbreaks can have significant impact on air quality (De Longueville et al. 2010; Querol et al. 2019; Votsis et al. 2020), and humans would be at an ever-increasing risk of frequent exposure to their adverse health effects (Fussell and Kelly 2021).

The human health effects of dust storms include respiratory disorders (e.g. asthma, tracheitis, pneumonia, seasonal allergic rhinitis and silicosis) cardiovascular disorders (e.g. stroke), conjunctivitis, inflammatory and allergic lung diseases, skin irritations, meningococcal meningitis, valley fever, diseases associated with toxic algal blooms and mortality and injuries related to transport accidents (Aghababaeian et al. 2021; Cheng et al. 2008; Fussell and Kelly 2021; Goudie 2014; Sadeghimoghaddam et al. 2021). Reviews and meta-analyses provided evidence for a positive association between desert dust exposure and mortality and hospital admissions for circulatory and respiratory events (Fussell and Kelly 2021; Giannadaki et al. 2014; Hashizume et al. 2020). Specifically, dust has been linked to chronic obstructive pulmonary disease, which is an umbrella term for progressive lung diseases including emphysema, chronic bronchitis, and refractory asthma (Fussell and Kelly 2021). Dust storms were suggested to be the cause of 15–50% of all cardiopulmonary deaths in the countries of the Sahara region, Middle East, South and East Asia (Giannadaki et al. 2014). Epidemics of meningococcal meningitis occur in the Sahelian region during the dry seasons with dusty conditions (Agier et al. 2012). Unfortunately, there are relatively fewer studies on the human health impacts of dust storms in the countries around the Sahara although the region is the most important source of desert sand and dust. On the other hand, a number of studies have documented that dust originating in the Sahara can impact air quality in many parts of the world like the western and eastern Mediterranean, Europe, the Caribbean, United States and South America (Karanasiou et al. 2012; Qor-el-aine et al. 2022). A study of the Saharan dust outbreak that took place between 14 and 19 of June 2020 concluded that the dust impacted a large area of the South, Southeast and East Coast of USA (Qor-el-aine et al. 2022).

6.2.3.2 Impacts on Climate and Ecosystems

There is a growing consensus that desertification can contribute to climate change through loss of vegetation and sand and dust storms. For example, reduced vegetation cover and more intense dust storms were found to intensify droughts (Cook et al. 2009). It can also modify the local climate by providing feedbacks, which can alter the carbon cycle, and hence the level of atmospheric CO_2 concentrations (Mirzabaev et al. 2019). These feedbacks can alter the surface energy and water budgets, directly impacting the local climate (Mirzabaev et al. 2019). Dust particles in the atmosphere can affect climate and weather directly and indirectly (Mahowald et al. 2010; Qor-el-aine et al. 2022). Directly through scattering and absorption, dust aerosols affect the radiative flux. Desert dust can perturb incoming solar and outgoing long wave radiation, thereby changing precipitation and temperature (Mahowald et al. 2010). Indirectly by influencing cloud formation as dust particles can act as cloud condensation nuclei (Creamean et al. 2013; Qor-el-aine et al. 2022). Through analysis of direct cloud and precipitation measurements, Creamean et al. (2013) showed that Saharan and Asian dust and aerosols could serve as ice nuclei and play an important role in orographic precipitation processes over the western United States.

There is also high confidence that desertification processes such as soil erosion, salinization, and overgrazing have negatively impacted ecosystem services in drylands, particularly food and fodder production (Mirzabaev et al. 2019). The loss of soil through erosion reduces soil nutrients and organic matter, thereby reducing land productivity. Reduced vegetation alters the soil surface, affecting the albedo and the water balance (Mirzabaev et al. 2019). On land without vegetation, winds will not have obstacles, and this favours dust storms and soil erosion. Soil erosion by wind results in a loss of fine soil particles and nutrient losses from the topsoil, which in turn reduce the ability of the soil to sequester carbon (Wiesmeier et al. 2015). Dust storms may also reduce crop yields due to plant damage caused by sandblasting (Field et al. 2010), exposure of roots and crop burial under sand deposits (Stefanski and Sivakumar 2009). Dust storms can also decrease the storage capacity of reservoirs by siltation and blockage of conveyance canals (Middleton 2017; Middleton and Kang 2017; Stefanski and Sivakumar 2009). This in turn can reduce crop production by reducing the quantity of water available for irrigation.

Desertification coupled with climate change is also negatively affecting livestock feed and grazing areas, forage quality, livestock productivity and consequently pastoral communities. Livestock productivity can reduce by injuries caused by dust storms (Stefanski and Sivakumar 2009). Reduced water retention capacity of degraded soils can amplify floods, reinforce degradation processes through soil erosion, and reduces annual intake of water to aquifers (Mirzabaev et al. 2019).

Desertification under climate change will threaten biodiversity in drylands (Mirzabaev et al. 2019).

6.2.3.3 Impact on Infrastructure

Dust storms and movement of sand dunes often threaten the safety and operation of railway and road infrastructure, and closures of railways, roads and airports due to reductions in visibility (Mirzabaev et al. 2019). There are numerous historical examples of how moving sand dunes have led to the forced decommissioning of early railway lines built in Sudan, Algeria, Namibia and Saudi Arabia in the late nineteenth and early twentieth centuries (Bruno et al. 2018). Currently, the highest concentrations of railways vulnerable to sand movements are located in north-western China, Middle East and North Africa (Bruno et al. 2018; Cheng and Xue 2014). In China, sand dune movements are periodically disrupting the railway transport on the Linhai–Ceke line in north-western China and on the Lanzhou–Xinjiang High-speed Railway in western China (Bruno et al. 2018). Sand and dust can also have significant impacts on aviation as it interferes with airport operations, aircraft maintenance and planning (Votsis et al. 2020, 2021).

There is also robust evidence for negatively effects of dust storms on the operation of solar and wind power harvesting equipment (Ghazi et al. 2014; Mirzabaev et al. 2019; Votsis et al. 2020, 2021). This often results from dust deposition, reduced reach of solar radiation and increasing blade-surface roughness, and reduced effective electricity distribution in high-voltage transmission lines (Mirzabaev et al. 2019; Votsis et al. 2021). Direct exposure to desert dust storm can reduce energy generation efficiency of solar panels by 70–80% in 1 h (Ghazi et al. 2014).

According to the existing evidence, there is high confidence that sand dune stabilization techniques can reduce sand and dust storms (Mirzabaev et al. 2019). Sand dunes may be stabilized through biological means (e.g. mulching, planting pasture grasses and woody perennials, agroforestry practices), mechanical (e.g. building palisades) and chemical (e.g. use of calcium bentonite or silica gel) means to fix mobile sand (Mirzabaev et al. 2019). To prevent dust transport and dust storms, soil exposure to wind must be managed. This can be done by protecting the soil surface with live or dead vegetation and minimizing the time and area of the soil that exposed. For example, crop residues used as mulch can stabilize the soil by reducing soil water loss and wind erosion. Michels et al. (1998) showed that covering the soil with 2 tons per ha of millet residues provides enough protection from sand storms. Mulching combined with trees has also been shown to protect the soil in the Sahel (Bayala et al. 2014). Mulching can also stabilize sand dunes. Once the dune surface is stabilized, it is crucial to establish permanent plant cover (Veste et al. 2006), woody perennials selected according to climatic and ecological conditions may be introduced. Such approaches have been successfully implemented on the shifting dunes in northern China (Veste et al. 2006; Yang et al. 2014). The challenge is to apply such approaches at large scales. In that regard, large national and transnational projects such as the green wall initiatives provide an untapped opportunity.

6.3 The Green Wall Initiatives

Green Wall (also called Green Dam) initiatives represent one of the classic examples of ecological engineering mega-projects implemented at national or transnational scales. Green Wall involves revegetation and afforestation implemented as part of national and international projects for tackling desertification. These initiatives have been implemented for a long time in China (Li et al. 2007; Zhao and Dai 2015) and Africa (Benhizia et al. 2021; Goffner et al. 2019). The Green Wall initiatives in China have been widely studied, and their outcomes have been rigorously assessed (Mirzabaev et al. 2019; Wang et al. 2013), providing evidence for improvements of ecosystem services such as soil erosion control, retention of water, drought mitigation, and biodiversity conservation (Wang et al. 2016; Xu et al. 2017). On the other hand, the outcomes of the initiatives implemented in the Sahel (i.e. the Great Green Wall) and North Africa (i.e. the green dam) have been poorly examined (Benhizia et al. 2021). The literature published on the different initiatives is briefly reviewed here and key findings will be discussed in the following sections.

6.3.1 The Green Walls of Africa

6.3.1.1 The Green Dam Initiative in Algeria

Following decades of land degradation in the High Plains bordering the Sahara Desert, Algerian authorities initiated the Green Dam project in 1972, a 3 million ha band of plantations running from east to west to stop the advance of the desert towards the north of the country (Benhizia et al. 2021). The project involved pine (*Pinus halepensis*) plantations extending across arid and semi-arid zones (300–200 mm isohyets) covering 1200 km long (from the Algerian–Moroccan border, to the Algerian–Tunisian border), with a width of about 20 km. The green dam inspired many African countries to build the Great Green Wall of the Sahara and the Sahel (Benhizia et al. 2021).

6.3.1.2 The Great Green Wall of the Sahara and the Sahel Initiative (GGWSSI)

The Sahel is located roughly between 11° and 18°N and experiences a strong north–south annual rainfall (200–800 mm) and vegetation (steppes to woodlands) gradients. It is a transition zone between the Sahara Desert and the savanna of the

Sudanean zone further south. With a rainy season lasting for only 3–4 months, it has a history of significant climatic variability, punctuated with significant droughts (O'Connor and Ford 2014). It is a very fragile ecosystem where climate variability have been the most apparent over the last four decades (Kaptué et al. 2015). The Sahel has experienced severe land degradation due to the combined effects of sandy soils, land use changes (e.g. farmland extensions by clearing of vegetation, overgrazing), and climate variability. The area is undergoing serious decline in tree density and biodiversity due to rapid land-degradation and desertification processes. Climate projections indicate that temperatures in the West Sahel are expected to increase by 3–6 °C by 2100, inter-annual variability in rainfalls will increase as well as occurrence of erratic rainfalls and extreme droughts and floods (IPCC 2014). It is projected that in a business-as-usual scenario, Chad and Niger could potentially lose their entire rain-fed agriculture by 2100 (IPCC 2019).

It is against this background that the Great Green Wall of the Sahara and the Sahel Initiative (GGWSSI) emerged as a pan-African effort in 2007 (Aigbokhaevbo 2013; Mbow 2017). This initiative aims to restore degraded arid landscapes, reduce the loss of biodiversity, mitigate and adapt to climate change, to improve livelihoods of populations in the Sahel and Sahara (Mbow 2017; Sacande 2018; UNCCD 2019). The wall passes through Djibouti, Eritrea, Ethiopia, Sudan, Chad, Niger, Nigeria, Mali, Burkina Faso, Mauritania and Senegal (Fig. 6.3a). It was initiated based on experience from earlier initiatives undertaken by various agencies to combat desertification in the different countries (see details in Mbow 2017). Those projects had recorded some success, which encouraged the Sahel nations and funding agencies to formulate the GGWSSI programme. For example, farmer-managed natural regeneration (FMNR) has produced successful results for desert reclamation where farmers regenerate land through protecting land from grazing, mulching, planting saplings of desired trees (see Chap. 3 in this book by Kuyah et al. 2022). The initiative was designed to be implemented over a period of 30 years with each phase lasting for 10 years with a projected budget estimated at US $1.6–2.4 billion (Aigbokhaevbo 2013). The initiative's restoration potential is estimated at 166 million hectares of arid and semi-arid lands in its agrosilvopastoral systems. The initiative aims to restore currently degraded land, reduce emissions, sequester 250 million tons of carbon to achieve Land Degradation Neutrality targets by 2030 (Berrahmouni et al. 2016; Sacande 2018). The GGW has a target of establishing plantations on 100 million hectares covering a distance of 7775 km from Senegal on the Atlantic coast to Eritrea on the Red Sea coast, with a width of 15 km.

The initiative is implemented at the level of each country by a national agency. Though the progress in implementation is slow due to lack of funding, a growing number of conflicts and insufficient capacities, the initiative has made some progress. It is reported that the initiative has restored 20 million hectares, mainly in Ethiopia, Nigeria, Senegal, and Sudan (UNCCD 2020). The literature perused indicates that current implementation focuses on large-scale tree planting although there are many integrated approaches for rehabilitation of degraded landscapes in the Sahel. These include dune stabilization, improving water-use efficiency through

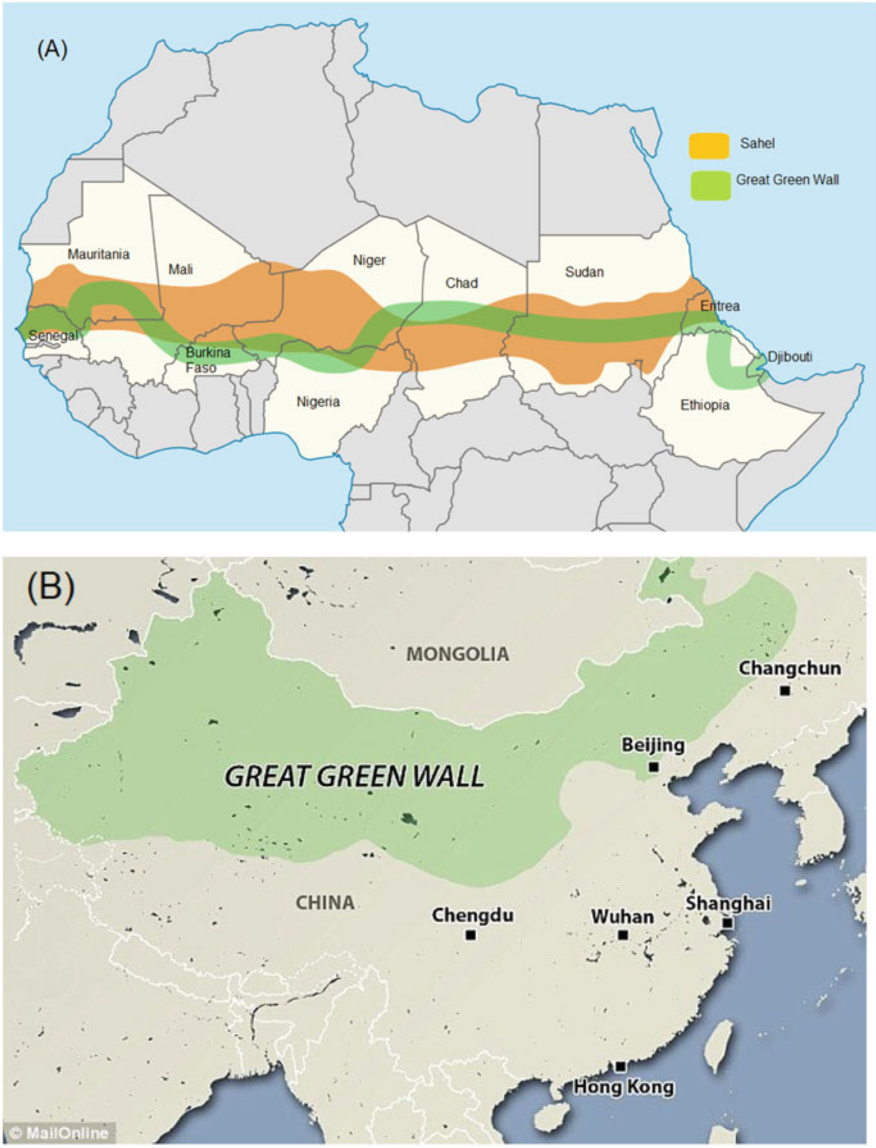

Fig. 6.3 The Great Green Wall of Africa (**a**) and the Green Great Wall of China (**b**). Source: (**a**) https://www.wikiwand.com/en/Desertification. Accessed 5 February 2022. (**b**) https://www.quora.com/. Accessed 5 February 2022

micro irrigation, water harvesting for livestock and sustainable management of water resources; promoting silvopastoral or agrosilvopastoral agroforestry practices.

6.3.2 The Green Great Wall of China

In 1978, the Chinese government implemented the 'Great Green Wall', a national ecological engineering effort of planting millions of trees along the 2800-mile (~4500 km) border of northern China's encroaching desert (Li et al. 2007; Parungo et al. 1994). China launched this initiative to address the problem of desertification and reduce eolian transport of dust from the Gobi Desert (Parungo et al. 1994). The project is anticipated to be going on until 2070 (Lu et al. 2018). So far, more than 66 billion trees have been planted. The major Green Wall initiatives in China include the Three-North Shelterbelt Project and the 'Sandstorm Source Control Project around Beijing and Tianjin' aimed at shielding northern and eastern agricultural ecosystems against sand and dust (Zhao and Dai 2015). Since the mid-1990s poplar plantations have intensified to combat desertification along the north-western border within Inner Mongolia. Different conifer species were also introduced. The trees were planted as shelterbelts, but they are also important for timber production and as a firewood source for local markets. In the North Shelter Forest alone, 5.4 million hectares of native trees were planted by 2010 (Lu et al. 2018).

Various studies show that in the regions covered by these initiatives, vegetation has greatly improved, while it varied dramatically outside the great green wall region. Parungo et al. (1994) noted a negative trend in dust-storm frequency and duration since the 1960s. Effects on atmospheric radiation and cloud microphysics appear to be statistically insignificant in the studied period. A study by Tan and Li (2015) showed that the programme greatly improved the vegetation index and effectively reduced dust storm intensity in northern China. The area of degraded land was reduced by 12,120 km^2 and the average annual occurrence of sandstorms decreased by 20.3% between 2009 and 2014 (Wang et al. 2013).

6.4 Opportunities for Mitigation Through Agroforestry

Historically, agroforestry has been practised in drylands in Africa and Asia (Boffa 1999; Dagar et al. 2020). Adopting agroforestry practices such as live fences, hedgerows, shelterbelts (windbreaks), scattered trees on crop land and silvopastoral systems is known to reduce wind erosion, while also providing additional benefits including carbon sequestration, edible and saleable products. Drawing on lessons from the Green Wall initiatives implemented in Africa and Asia and the broader literature from drylands, this section attempts to identify appropriate agroforestry practices.

6.4.1 Live Fences, Hedgerows and Riparian Buffer Strips

Live fences refer to lines of trees grown to delineate boundaries of farms or farm components, such as homesteads, crop fields, pasture plots and animal enclosures. When established with multipurpose trees, these can provide fuelwood, poles, timber, green manure or mulch and animal fodder. The trees in live fences may be pruned, pollarded or coppiced depending on the species and type of product desired. In the Sahel, trees such as *Ziziphus mauritiana, Combretum micranthum* and *Balanites aegyptiaca* are planted with other tree and shrub species to make live fences that protect crops against browsing animals because of their thorns (Kalinganire et al. 2008). Live fences are used to circumvent the limitation of the traditional dead fences; where farmers cut branches from thorny trees and arrange them in a continuous band around the area to be protected. Live fences are a sustainable alternative to dead fences as the latter has to be established every year due to termite destruction, reuse of the branches as firewood and depletion of branches where large farms are involved. Depending on the species planted, live fences also act as windbreaks (Ndayambaje and Mohren 2011). The trees can stabilize the soil and control wind and water erosion, while also storing large quantities of carbon in their biomass and soil.

Evidence in West Africa shows that live fences are multifunctional and are valued as much for their products as their protective function. In Ségou, Mali, households and neighbouring families benefited from live fences by harvesting henna from *Lawsonia inermis*, medicinal products for stomach and mouth pain from *Z. mauritiana, Bauhinia rufescens* and *Acacia nilotica*; fruits from *Z. mauritiana* and extracting tannin from fruits of *Acacia nilotica* (Levasseur et al. 2004). Households with surplus products (e.g. henna, medicines) sold them for income (Levasseur et al. 2004). In addition, species such as *Erythrina* and *Ficus* grow to become shade trees that protect animals from the sun. Even though maintenance of live fence is labour intensive, its multipurpose nature makes it appealing to resource poor households.

Hedgerows are strips of permanent vegetation (grasses, trees or shrubs) in or around the borders of crop fields or near water courses (Borin et al. 2010). A distinctive feature of hedgerows is that one or more rows of trees or shrubs are planted closely to form a continuous barrier on the area of interest; unlike live fence where trees are planted at greater distances. The primary purpose of hedges is to intercept the runoff and hence to minimize the loss of soil and nutrients from crop lands, whereas buffer strips serve in both interception and filtration of runoff water and preventing stream bank erosion. Hedgerows and buffer strips have many other roles including reduction of wind speed, protection of water quality, carbon sequestration, biomass production, habitat for biodiversity (Haddaway et al. 2018). They can also act as windbreaks and reduce the impact of wind and protect crops and soil from wind damage. Hiernaux et al. (2019) mapped woody field hedges within a 435 km^2 agricultural area in Dantiandou, south-western Niger and found an increase in density of woody field hedges per area of agricultural land, reaching 5.56 km^{-2} in

2016. The study shows that woody field hedges increased by a mean annual rate of 3.7% from 1992 to 2016 (Hiernaux et al. 2019). The trees and shrubs occurred at a density of 2.2 trees and 14.3 shrubs per 100 m of field hedges, respectively, and stood at an average of 5–6 m apart along the hedge (Hiernaux et al. 2019).

6.4.2 Shelterbelts (Windbreaks)

A shelterbelt or windbreak consists of multiple rows of trees that block or redirect wind, and provide shelter for crops and pastures from winds. Even though shelterbelts are a form of agroforestry, a recent publication on desertification (Mirzabaev et al. 2019) referred to agroforestry and shelterbelts as separate entities. The primary function of shelterbelts is wind reduction, although some may be established for other 'non-wind' purposes such as provision of shade for livestock, aesthetic and recreational value, wood and non-timber products. Shelterbelts designed for wind reduction can regulate microclimate resulting in moderate soil and air temperature, increase in relative humidity, and reduced evaporation and increased soil moisture. The outcome depends on the planting pattern, the design (height, length and density) of the windbreak, location and the tree species. Trees are usually planted perpendicular to the prevailing wind direction, or, if winds occur in more than one direction, planting should be done in a crisscross pattern. Fast-growing tree species, adapted to the local climate and soil, are used. Tree species that have economic value in the form of timber, fuel, fruits or nuts are best suited for this purpose. For example, fast-growing native species of poplars (e.g. *Populus pseudosimonii*, *P. simonii*) and exotic (e.g. *P. deltoides*, *P. trichocarpa* and *P. nigra*) are grown in the shelterbelts in the Green Great Wall of China (Veste et al. 2006). Similarly, in the Green Dam initiative in Algeria, pines (*Pinus halepensis*) were planted.

When properly designed, windbreaks can enhance and diversify income opportunities from timber production, modify microclimate and provide habitat for plants and animals. Depending upon the species of tree and age, shelterbelts offer an opportunity to sequester more carbon in the soil than in cropped soils (Dhillon and Van Rees 2017).

The Great Green Wall initiative in Africa is essentially a set of windbreaks across Africa (UNCCD 2022). Windbreaks have greater potential for medium/long-term mitigation because their services (protection of crops and livestock from strong wind and control of soil erosion) have greater influence compared to wood or non-wood products. Increased crop yields due to improved protection from the wind may lead to greater organic matter returns to the soil and increased soil sequestration. Shelterbelts in China have been shown to increase crop production due to prevention of wind erosion and wind damage, and reduced evapotranspiration. For example, maize yield increased by 6% due to shelterbelts in North West China (Zheng et al. 2016). Windbreaks generally increase crop yields in the protected fields, despite reduction in growth of crops near the tree rows that is evident in most windbreaks (Onyewotu et al. 2004). Farmers in Bankass, Mali attributed high millet yields to physical protection of soils in places where wind had previously buried millet shoots, leading to lower yields (Allen et al. 2009). Much of the empirical evidence on productivity of windbreaks (Lamers et al. 1994) and their effects on crop yield (Onyewotu et al. 2004; Michels et al. 1998) is based on research from the 1990s.

6.4.3 Scattered Trees on Crop Land and Parkland Management

Scattered trees are especially important for protecting croplands and pasture in drylands. Scattered trees dot croplands and other land use systems in all the African countries where the Green Great Wall initiative is implemented. The trees are either a remnant of natural forests after conversion to other land uses or were regenerated after the land was cleared or were actively planted by farmers. Farmer managed natural regeneration (FMNR) has emerged as the most promising and one of the leading ways in which farmers raise trees in crop fields and parklands (see FMNR chapter). Local communities manage different species on farms and communal grazing land as part of their way of life. *Faidherbia albida*, shea tree (*Vitellaria paradoxa*), baobab (*Adansonia digitata*) are the most common trees that farmers maintain for various products and services in the Sahel.

Parklands are generally considered as landscapes in which remnant trees occur scattered in cultivated or recently fallowed agricultural fields (Boffa 1999). Livestock production may be a significant or secondary component in these systems. FMNR is the mechanism by which tree stands are traditionally maintained in parklands (chapter in this book by Kuyah et al. 2022). Some parklands abound with single specific stands of *Faidherbia albida* (for example in Bambey in Senegal, N'Dounga in Niger, Yagoua in Cameroun and Mayo Kebi in Chad) or *Borassus aethiopum*; other parklands have a mix of the dominant species and a range of other trees and shrubs. There are a variety of reasons why trees are managed in farms, for example fruit trees are usually planted and managed on farmland for provision of tree foods. In the Sahel, the most prominent fruit trees include *Vitellaria paradoxa* (shea tree), baobab (*Adansonia digitata*), marula (*Sclerocarya birrea*) and Ziziphus. A number of projects dealing with formal domestication of indigenous fruit tree species have been undertaken in West Africa including the Sahel (Akinnifesi et al. 2008). Lessons on value addition and marketing have been documented in Akinnifesi et al. (2008).

The harsh conditions in drylands create challenges for crop growth. Trees in parklands mitigate these risks by lowering temperatures and providing shade (Bayala et al. 2014). By reducing windspeed and shading, parkland trees mitigate temperature extremes, control wind erosion and reduce loss of water through evapotranspiration. In a farmer's field in Dori, Burkina Faso, shrubs (*Hyphaene thebaica, Commiphora africana* and *Ziziphus mauritiana*) reduced wind speed near the surface by an average of about 25% for a distance of up to about seven times the height of the shrub (Leenders et al. 2007). A combination of these shrubs and trees (e.g., *Adansonia digitata* and *Faidherbia albida*) were found to be effective for reducing soil loss, directly by trapping sand particles near the surface and indirectly by reducing the speed of wind on the leeward (Leenders et al. 2007). Similarly, Jonsson et al. (1999) observed reduction in windspeed and soil evaporation under *Parkia biglobosa* and *Vitellaria paradoxa* trees in Burkina Faso. With proper management, the effect of improved microclimate and soil fertility can make up for the negative effects of competition between trees and crops. The ability of the parklands to enhance and stabilize crop production has been much studied over the past three decades (Boffa 1999; Bayala et al. 2014; Sileshi 2016). Using a meta-analysis of 15 studies conducted in Burkina Faso, Mali, Niger and Senegal, Bayala et al. (2012) reported that parkland trees increase crop yields by 140–240 kg ha^{-1} depending on tree species. The yields can further be enhanced through crown pruning or by using shade-tolerant crops. Introducing locally adapted trees that can provide the economic incentive to poor farmers who are otherwise reluctant to plant trees, will further enhance their confidence in sustainable intensification of agriculture using agroforestry and livelihood security.

6.4.4 Silvopastoral Systems

Silvopastoral systems involve the intentional integration of trees, forage crops and livestock in an intensively managed system. Two broad forms of silvopasture are common in the drylands of Africa. The first is grazing systems, where animals move freely and graze under trees scattered on pasture land. This is common in agroforestry parkland where animals roam and graze under parkland trees such as *Balanites aegyptiaca*, *Faidherbia albida* and *Pterocarpus erinaceus*. The second form is fodder tree system, where branches of trees are lopped to provide foliage and pods for livestock, which may be stall-fed (Melesse et al. 2019). For example, in the Sahel, *Faidherbia albida* and *Parkia biglobosa* are commonly lopped and fed to livestock during the scarcity in dry season. Feeding animals with fodder from trees grown somewhere else is a common practice among smallholder farmers in Africa. Silvopastoral systems can be combined with sustainable grazing approaches. There is high confidence that sustainable grazing approaches and re-vegetation can increase rangeland productivity (Mirzabaev et al. 2019).

In the drylands of Africa where the GGWSSI is implemented, livestock forms a major component of pastoral and agro-pastoral production systems. Unfortunately, grazing lands across these drylands are being overgrazed and degraded, or being converted to commercial crops such as cotton. This has limited the opportunities for migratory pastoral communities (Dimelu et al. 2016; Tamou et al. 2018). Policies such as enforced sedentarization, and in certain cases protected areas (fencing), which restrict livestock mobility have hampered optimal use of grazing land resources (Du 2012). Under the GGWSS initiative, now many areas are being protected from grazing to increase the green cover. Restrictions on the mobile lifestyle of nomadic populations can reduce their adaptive capacity and threaten pastoral livelihoods (Dimelu et al. 2016; Tamou et al. 2018). In that sense, silvopastoral systems may become a viable alternative for sustainable intensification of grazing lands, holding promise for short-term income from livestock and long-term returns from trees and tree products. Available evidence suggests that silvopastoral systems can increase forage and livestock production, while providing several environmental benefits (Jose and Dollinger 2019).

The trees provide shelter and shade for livestock and herdsmen, and protect the animals from strong wind. Shading can reduce stress associated with extreme heat and increase feed efficiency, which can increase milk production and weight gain. In drylands of Africa, shading is known to moderate microclimate (Bayala et al. 2014). Livestock droppings pile up where the animals rest creating spots of high soil fertility near the trees, improved soil fertility coupled with favourable microclimate and increase productivity (Sileshi 2016).

Silvopasture holds great potential for other benefits beyond the farm; increased biodiversity, carbon sequestration, protection of water quality and control of soil erosion. On the contrary, livestock allowed to graze among trees that are not consciously managed silvopasture contribute to degradation of dryland ecosystem (Pricope et al. 2013), for example, through browsing and trampling sapling and seedlings, and can cause soil and water quality problems through compaction and soil erosion. The concept of rehabilitation of degraded lands by establishment of live fences enclosures and intensive agroforestry after protection from grazing has been used successfully in West Pokot in Kenya (Wairore et al. 2016) and Northern Ethiopia (Mengistu et al. 2005). Establishment of enclosures and agroforestry alleviated pasture scarcity allowing the local pastoral community to participate in crop production (Wairore et al. 2016).

6.5 Challenges

6.5.1 Socio-Ecological Complexity

Restoration efforts such as the Great Green Wall initiatives are not just about planting trees, but they involve landscape-scale restoration of contiguous or fragmented ecosystem (Menz et al. 2013). This often takes place in complex and unpredictable socio-ecological contexts, involving multiple stakeholders and interests, where local actions aggregate into a broader context that considers landscape flows and connectivity. In policy actions, the scientific support behind less-popular options may have been ignored or simply may not be available. It is in that context that agroforestry practices are often promoted. Therefore, investment in scaling up agroforestry practices may be relegated to the back seat due to other competing interests or lack of information. Institutions involved in the research and development of agroforestry need to be actively involved in providing evidence-based practices, scalable solutions suited to specific types of drylands, technical know-how and capacity development to deliver results. Such institutions should also be able to provide guidance on which agroforestry practices can be promoted with confidence.

6.5.2 Cost of Implementation

The promotion of agroforestry is costly and has had a long history of uncertain funding. Large restoration efforts such as the Green Wall initiatives will require even a greater investment (Li et al. 2007; Mirzabaev et al. 2022). For example, the cost of tree planting in the 'Great Green Wall' programme of China was estimated at US\$ 383 ha^{-1} (Li et al. 2007). Similarly, Mirzabaev et al. (2022) assessed the costs and benefits of the Great Green Wall of Africa and found that an investment of US\$44 billion is needed under the base scenario (US\$18–70 billion across scenarios) to fund all proposed land restoration activities. The global community pledged US\$14.3 billion for implementation of the GGWSSI during the One Planet Summit for Biodiversity in 2021 (Mirzabaev et al. 2022). Without these huge external investments, governments may not be able to afford this level of investment.

6.5.3 Policy Challenges

Significant advances in adaptation have been made over the last decade, including the establishment and disbursement of adaptation funds through the UN Framework Convention on Climate Change (UNFCCC), completion of National Adaptation Programs of Action (NAPAs), initiation of National Adaptation Plans (NAPs), mainstreaming of adaptation into development projects. However, many of the national policies and plans of action do not include agroforestry in either adaptation or mitigation strategies. For example, only five countries (Burkina Faso, Chad, Djibouti, Ethiopia and Niger) out of the 11 countries implementing the African Great Green Wall have mentioned agroforestry in their Nationally Determined Contributions (see chapter in this book by Duguma et al. 2022). Experience in the Sahel has shown that where policies and incentives are favourable, farmers have themselves encouraged the natural regeneration of trees and adopting agroforestry practices suited to their circumstances. As a result, vast areas are now under tree cover especially in Senegal and Niger. The green wall initiatives need to develop supportive policies and incentives to assure replication in countries where such interventions are being initiated.

For agroforestry to be mainstreamed into government planning, it is crucial to create awareness and raise its profile. This needs to be done proactively in policy fora. It is also important to undertake appraisal of policies governing land and tree tenure so that institutional constraints to tree planting can be reduced and supportive policies can be enacted.

6.5.4 Scarcity of Planting Materials

Lack of planting materials has been frequently cited by farmers as the major constraint to planting trees. The absence of reliable supply of planting materials is also the most important concerns for programmes that try to scale up agroforestry (Nyoka et al. 2011). Unlike annual crops, there is no established market or industry to make tree seeds available off the shelf to potential users. The quantities of tree seeds required at any given time or location are also not sufficiently large to stimulate large-scale investment by seed companies (Nyoka et al. 2011). Lack of storage facilities and markets means that seeds need to be produced locally. To overcome these challenges, it is important to organize farmers to produce tree seeds, seedlings and other planting materials. Tree seed supply could be improved by strengthening of grass-root organizations involved in tree seed production and distribution through farmer-to-farmer exchange (Nyoka et al. 2011). There is also a need to support seed storage facilities within communities.

6.5.5 Scarcity of Water

Implementing agroforestry projects in drylands is often constrained by scarcity of water (Apuri et al. 2018) as newly planted trees often die of drought (Li et al. 2007). This could be a greater challenge especially in the face of climate change, which is projected to reduce water availability. The African countries where the green wall initiatives are implemented are historically water-deficit areas. Figure 6.4a shows the map of the reference annual water deficit, which measures the discrepancy between evaporative demand of a well-watered vegetation and the actual moisture supply under rain-fed conditions for the period 1981–2010 (Fischer et al. 2021). Scarcity of water may also be further aggravated by the shortening of the growing period with future climate change. Figure 6.4b presents a map of the reference length of growing period simulated for average 30-year climate (Fischer et al. 2021), for historical years (1961–2010) and for projected future climates of the period (2011–2099).

There are significant concerns that climate change will increase the frequency or severity of drought events in the future (Cook et al. 2020). The latest state-of-the-art climate model projections from CMIP6 show drying and increases in extreme drought occurrence across many regions by the end of the twenty-first century even under the most aggressive climate mitigation pathways (Cook et al. 2020). Regular watering and protection of seedlings from drought is needed for successful establishment of trees in shelterbelts and silvopastoral systems. In the drier areas adoption of tree planting integrated with Zai pit may also increase the chances of seedling survival. Careful planting of seedlings in safe sites such as around termite mounds may also increase the likelihood of tree establishment (Bonachela et al. 2021; Sileshi et al. 2010). In drylands, termite mounds essentially act as islands of fertility and safe sites for tree regeneration (Sileshi et al. 2010). For example, in the

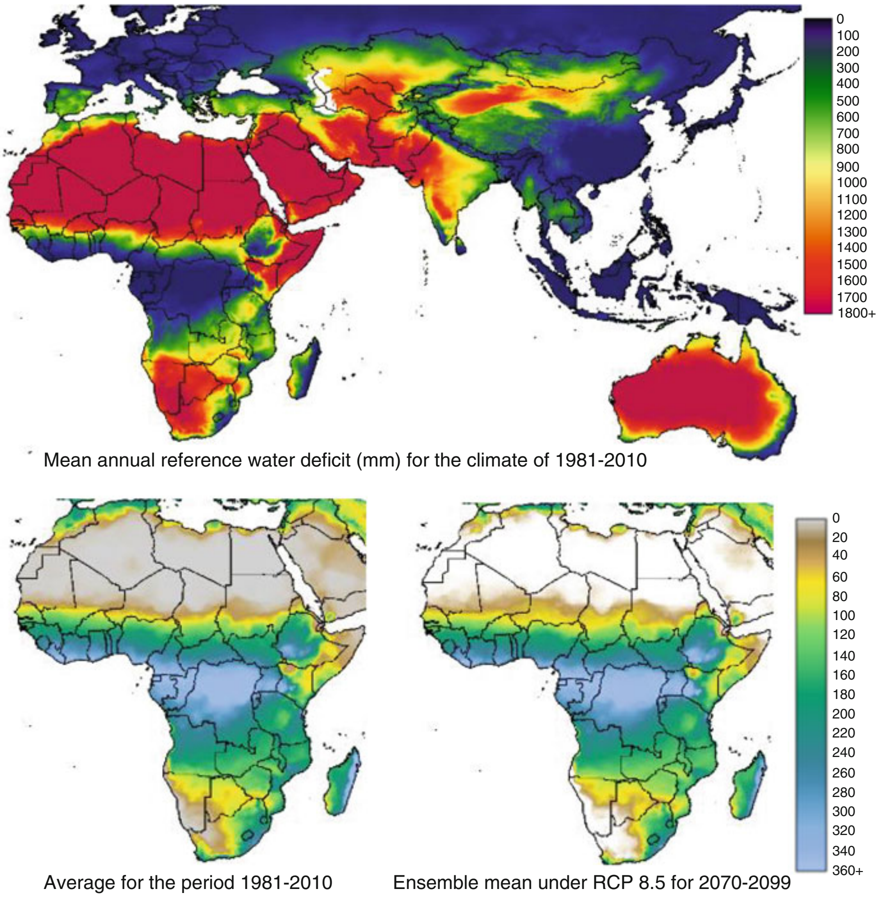

Fig. 6.4 Map of water deficit (**a**) and projected changes in the reference length of the growing period (**b**). Adapted from Fischer et al. (2021)

drylands of Namibia, *Macrotermes* colonies acted as a 'water-gathering system' drawing water from a broad expanse of soil towards the nest (Trabucco and Zomer 2019). The microtopography created by termite mounds also plays a significant role in the water economy of semi-arid savannas (Sileshi et al. 2010).

On the other hand, expansion of tree planting in water-limited areas can create conflicting demands for water between the ecosystem and humans. Empirical evidence suggesting that large-scale planting of trees can cause water scarcity as they could change the water balance (Bentley and Coomes 2020; Feng et al. 2016; Li et al. 2007; Wilske et al. 2009). Tree planting could also exhaust groundwater resources in arid regions (Li et al. 2007). For example, within Inner Mongolia it has been established that this can significantly change the water balance in the area (e.g. high ET at the cost of a reduction in the water table), which renders large-scale plantations counterproductive (Wilske et al. 2009). Similarly, in the Loess Plateau of

China, Feng et al. (2016) found that the new planting had increased evapotranspiration that induced a significant decrease in the ratio of river runoff to annual precipitation across hydrological catchments. In a study covering 43 sites across the world where forests have been established, river flow reduced by an average of 25% within 5 years of planting trees. River flow reduced by an average of 40% by the 25th year or in a few cases rivers had dried up (Bentley and Coomes 2020). These observations highlight the needs to critically consider potential competitions and conflicts for water when initiating practices such as shelterbelts.

6.6 Conclusion and Way Forward

Desert dust plays an important role in different aspects of weather, climate and atmospheric chemistry, and has a significant impact on air quality, not only in areas close to the source points or regions but over areas thousands of kilometres distant. Epidemiological studies and meta-analyses from affected areas provide substantial evidence for severe health hazards, hospital admissions and mortality due to exposure to desert dust. This calls for treating desertification as an environmental and human health imperative and substantial investment in mitigation measures such as agroforestry. The Green Wall initiatives in Africa and Asia provide opportunities to integrate agroforestry into the development projects and attract investment at the local and global levels. However, significant challenges exist in terms of evidence-based policies and practices. We therefore recommend institutions involved in the research and development of agroforestry to actively engage and provide guidance and scalable solutions as well as in capacity development to deliver results.

References

Aghababaeian H, Ostadtaghizadeh A, Ardalan A, Asgary A, Akbary M, Yekaninejad MS, Stephens C (2021) Global health impacts of dust storms: a systematic review. Environ Health Insights 15: 11786302211018390. https://doi.org/10.1177/11786302211018390

Agier L, Deroubaix A, Martiny N, Yaka P, Djibo A, Broutin H (2012) Seasonality of meningitis in Africa and climate forcing: aerosols stand out. J R Soc Interface 10(79):20120814. https://doi.org/10.1098/rsif.2012.0814

Aigbokhaevbo VO (2013) The “great green wall”: implementation constraints. Environ Policy Law 44(6):330–355

Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (2008) Indigenous fruit trees in the tropics- domestication, utilization and commercialization. CAB International, Wallingford

Allen M, Diakite M, Gana I (2009) Regreening the Sahel: a case study of farmer managed natural regeneration in Mali. Sahel Eco, Bamako

Apuri I, Peprah K, Achana GTW (2018) Climate change adaptation through agroforestry: the case of Kassena Nankana West District, Ghana. Environ Dev 28:32–41. https://doi.org/10.1016/J.ENVDEV.2018.09.002

Bayala J, Sileshi G, Coe R, Antoine K, Tchoundjeu Z, Sinclair F, Garrity GP (2012) Cereal yield response to conservation agriculture practices in drylands of West Africa: a quantitative synthesis. J Arid Environ 78:13–25

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Benhizia R, Kouba Y, Szabó G, Négyesi G, Ata B (2021) Monitoring the spatiotemporal evolution of the green dam in Djelfa Province, Algeria. Sustain For 13:7953. https://doi.org/10.3390/su13147953

Bentley L, Coomes DA (2020) Partial river flow recovery with forest age is rare in the decades following establishment. Glob Chang Biol. https://doi.org/10.1111/gcb.14954

Berdugo M, Delgado-Baquerizo M, Soliveres S, Hernández-Clemente R, Zhao Y, Gaitán JJ, Gross N, Saiz H, Maire V, Lehmann A, Rillig MC, Sole RV, Maestre FT (2020) Global ecosystem thresholds driven by aridity. Science 367:787–790

Berrahmouni N, Laestadius L, Martucci A, Mollicone D, Patriarca C, Sacande M (2016) Building Africa's great green wall restoring degraded drylands for stronger and more resilient communities. Food and Agriculture Organization of the United Nations (FAO), Rome

Boffa J-M (1999) Agroforestry parklands in sub-Saharan Africa. Food and Agriculture Organization of the United Nations (FAO), Rome

Bonachela JA, Pringle RM, Sheffer E, Coverdale TC, Guyton JA, Caylor KK, Levin SA, Tarnita CE (2021) Termite mounds can increase the robustness of dryland ecosystems to climatic change. Science 347:651–655

Borin M, Passoni M, Thieni M, Tempesta T (2010) Multiple functions of buffer strips in farming areas. Eur J Agron 32(1):103–111

Bruno L, Horvat M, Raffaele L (2018) Windblown sand along railway infrastructures: a review of challenges and mitigation measures. J Wind Eng Ind Aerodyn 177:340–365. https://doi.org/10.1016/J.JWEIA.2018.04.021

Cheng J, Xue C (2014) The sand-damage–prevention engineering system for the railway in the 37 desert region of the Qinghai-Tibet plateau. J Wind Eng Ind Aerodyn 125:30–37. https://doi.org/10.1016/J.JWEIA.2013.11.016

Cheng MF, Ho SC, Chiu HF, Wu TN, Chen PS, Yang CY (2008) Consequences of exposure to Asian dust storm events on daily pneumonia hospital admissions in Taipei, Taiwan. J Toxicol Environ Health A 71:1295–1299. https://doi.org/10.1080/15287390802114808

Cherlet M, Hutchinson C, Reynolds J, Hill J, Sommer S, von Maltitz G (2018) World atlas of desertification. Publication Office of the European Union, Luxembourg

Cook BI, Miller RL, Seager R (2009) Amplification of the North American "dust bowl" drought through human-induced land degradation. Proc Natl Acad Sci U S A 106(13):4997–5001

Cook BI, Mankin JS, Marvel K, Williams AP, Smerdon JE, Anchukaitis KJ (2020) Twenty-first century drought projections in the CMIP6 forcing scenarios. Earth Future 8:e2019EF001461. https://doi.org/10.1029/2019EF001461

Creamean JM, Suski KJ, Rosenfeld D, Cazorla A, DeMott PJ, Sullivan RC, White AB, Ralph FM, Minnis P, Comstock JM, Tomlinson JM, Prather KA (2013) Dust and biological aerosols from the Sahara and Asia influence precipitation in the Western US. Science 339:1572–1578. https://doi.org/10.1126/science.1227279

Dagar JC, Gupta SR, Teketay D (eds) (2020) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, p 554

De Longueville F, Hountondji Y-C, Henry S, Ozer P (2010) What do we know about effects of desert dust on air quality and human health in West Africa compared to other regions? Sci Total Environ 409:1–8. https://doi.org/10.1016/j.scitotenv.2010.09.025

de Longueville F, Ozer P, Doumbia S, Henry S (2013) Desert dust impacts on human health: an alarming worldwide reality and a need for studies in West Africa. Int J Biometeorol 57:1–19. https://doi.org/10.1007/s00484-012-0541-y

Dhillon GS, Van Rees KCJ (2017) Soil organic carbon sequestration by shelterbelt agroforestry systems in Saskatchewan. Can J Soil Sci 2017:1–16. https://doi.org/10.1139/cjss-2016-0094
Dimelu M, Salifu E, Igbokwe E (2016) Resource use conflict in agrarian communities, management and challenges: a case of farmer-herdsmen conflict in Kogi State, Nigeria. J Rural Stud 46:147–154
Donat MG, Lowry AL, Alexander LV, O'Gorman PA, Maher N (2016) More extreme precipitation in the world's dry and wet regions. Nat Clim Chang 6(5):508–513. https://doi.org/10.1038/nclimate2941
Du F (2012) Ecological resettlement of Tibetan herders in the Sanjiangyuan: a case study in Madoi County of Qinghai. Nomadic Peoples 16(1):116–133. https://doi.org/10.3167/np.2012.160109
Duguma LA, Minang PA, Watson C, Nath AJ, Muthee KW, van Noordwijk M, Mutune JM, Sileshi GW (2022) Agroforestry as a key intervention to achieve Nationally Determined Contribution (NDC) targets. In: Dagar JC, Gupta SR, Sileshi GW (eds) Agroforestry for sustainable intensification of agriculture in Asia and Africa. Springer, Cham
FAO and ITPS (2021) Recarbonizing global soils: A technical manual of recommended management practices. Volume 2: hot spots and bright spots of soil organic carbon. FAO, Rome
Feng X, Fu B, Piao S, Wang S, Ciais P, Zeng Z, Lü Y, Zeng Y, Li Y, Jiang X, Wu B (2016) Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat Clim Chang 6:1019–1022. https://doi.org/10.1038/nclimate3092
Field JP, Belnap J, Breshears DD, Neff JC, Okin GS, Whicker JJ, Reynolds RL (2010) The ecology of dust. In: Frontiers in ecology and the environment. Wiley, Hoboken
Field CB, Barros VR, Mach KJ, Mastrandrea MD, van Aalst M, Adger WN, Arent DJ, Barnett H, Betts R, Bilir TE, Birkmann J, Carmin J, Chadee DD, Challinor AJ, Chatterjee M, Cramer W, Davidson DJ, Estrada YO, Gattuso JP, Hijioka Y, Hoegh-Guldberg O, Huang HQ, Insarov GE, Jones RN, Kovats RS, Romero-Lankao P, Larsen JN, Losada IJ, Marengo JA, McLean RF, Mearns LO, Mechler R, Morton JF, Niang I, Oki T, Olwoch JM, Opondo M, Poloczanska ES, Pörtner HO, Redsteer MH, Reisinger A, Revi A, Schmidt DN, Shaw MR, Solecki W, Stone DA, Stone MR, Strzepek KM, Suarez AJ, Tschakert P, Valentini R, Vicuña S, Villamizar A, Vincent KE, Warren R, White LL, Wilbanks TJ, Wong PP, Yohe GW (2014) Technical summary. Climate change 2014: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge
Fischer G, Nachtergaele FO, van Velthuizen HT, Chiozza F, Franceschini G, Henry M, Muchoney D, Tramberend S (2021) Global agro-ecological zones v4 – model documentation. FAO, Rome. https://doi.org/10.4060/cb4744en
Fussell JC, Kelly FK (2021) Mechanisms underlying the health effects of desert sand dust. Environ Int 157:106790. https://doi.org/10.1016/j.envint.2021.106790
Ghazi S, Sayigh A, Ip K (2014) Dust effect on flat surfaces – a review paper. Renew Sust Energ Rev 33:742–751. https://doi.org/10.1016/J.RSER.2014.02.016
Giannadaki D, Pozzer A, Lelieveld J (2014) Modeled global effects of airborne desert dust on air quality and premature mortality. Atmos Chem Phys 14(2):957–968. https://doi.org/10.5194/acp-14-957-2014
Goffner D, Sinare H, Gordon LJ (2019) The great green wall for the Sahara and the Sahel initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. Reg Environ Chang 19:1417–1428
Goudie AS (2014) Desert dust and human health disorders. Environ Int 63:101–113. https://doi.org/10.1016/j.envint.2013.10.011
Griffin DW, Garrison VH, Herman JR, Shinn EA (2001) African desert dust in the Caribbean atmosphere: microbiology and public health. Aerobiologia 17:203–213
Haddaway NR, Brown C, Eales J, Eggers S, Josefsson J, Kronvang B (2018) The multifunctional roles of vegetated strips around and within agricultural fields. Environ Evid 2018:7–14
Hashizume M, Kim Y, Ng CFS, Chung Y, Madaniyazi N, Bell ML, Guo YL, Kan H, Honda Y, Yi SM, Kim H, Nishiwaki Y (2020) Health effects of Asian dust: a systematic review and meta-analysis. Environ Health Perspect 128:6

Hiernaux P, Adamou K, Moumouni O, Turner MD, Tong X, Savadogo P, Mougin E, Malam IO (2019) Expanding networks of field hedges in densely populated landscapes in the Sahel. For Ecol Manag 440:178–188

Ho FK, Wu KC, Niu X, Wu Y, Zhu CS, Wu F, Cao J, Shen Z, Hsiao T, Chuang K, Chuang H (2019) Contributions of local pollution emissions to particle bioreactivity in downwind cities in China during Asian dust periods. Environ Pollut 245:675–683

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I (2018a) Chapter 3: impacts of 1.5°C global warming on natural and human systems. In: Global final government distribution chapter 3 IPCC SRCCL subject to copy-editing. IPCC, Geneva

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I (2018b) Chapter 3: impacts of 1.5°C global warming on natural and human systems. In: Global warming of 1.5°C. IPCC, Geneva

Huang J, Yu H, Guan X, Wang G, Guo R (2016) Accelerated dryland expansion under climate change. Nat Clim Chang 6:166–171. https://doi.org/10.1038/nclimate2837

IPCC (2014) Impacts, adaptations and vulnerability, Intergovernmental Panel on Climate Change Assessment report 5

IPCC (2019) Special report on climate change and land-Desertification. Chapter 3. Intergovernmental Panel on Climate Change, Final for Government Distribution, p 174

Jiang H (2016) Taking down the "Great Green Wall": the science and policy discourse of desertification and its control in China. In: Behnke R, Mortimore M (eds) The end of desertification? Springer earth system sciences. Springer, Berlin. https://doi.org/10.1007/978-3-642-16014-1_19

Jonsson K, Ong CK, Odongo JCW (1999) Influence of scattered nere and karite trees on microclimate, soil fertility and millet yield in Burkina Faso. Exp Agric 35:39–53

Jose S, Dollinger J (2019) Silvopasture: a sustainable livestock production system. Agrofor Syst 93(1):1–9

Kalinganire A, Weber J, Uwamariya A, Kone B (2008) Improving rural livelihoods through domestication of indigenous fruit trees in the parklands of the Sahel. In: Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utilization and commercialization. CABI, Wallingford, pp 186–203

Kaptué AT, Prihodko L, Hanan NP (2015) On regreening and degradation in Sahelian watersheds. Proc Natl Acad Sci U S A 112:12133–12138. https://doi.org/10.1073/pnas.1509645112

Karanasiou A, Moreno N, Moreno T, Viana M, de Leeuw F, Querol X (2012) Health effects from Sahara dust episodes in Europe: literature review and research gaps. Environ Int 47:107–114. https://doi.org/10.1016/j.envint.2012.06.012

Koutroulis AG (2019) Dryland changes under different levels of global warming. Sci Total Environ 655:482–511. https://doi.org/10.1016/J.SCITOTENV.2018.11.215

Kuyah S, Buleti S, Dimobe K, Nkurunziza L, Moussa S, Muthuri C, Oborn I (2022) Farmer managed natural regeneration in Africa: evidence for climate change mitigation and adaptation in drylands. In: Dagar JC, Gupta SR, Sileshi GW (eds) Agroforestry for sustainable intensification of agriculture in Asia and Africa. Springer, Cham

Lamers J, Michels K, Vandenbeldt R (1994) Trees and windbreaks in the Sahel: establishment, growth, nutritive, and calorific values. Agrofor Syst 26:171–184

Lawrence PG, Maxwell BD, Rew LJ, Ellis C, Bekkerman A (2018) Vulnerability of dryland agricultural regimes to economic and climatic change. Ecol Soc 23:34. https://doi.org/10.5751/ES-09983-230134

Leenders JK, van Boxel J, Sterk G (2007) The effect of single vegetation elements on wind speed and sediment transport in the Sahelian zone of Burkina Faso. Earth Surf Process Landf 32:1454–1474

Levasseur V, Djimdé M, Olivier A (2004) Live fences in Ségou, Mali: an evaluation by their early users. Agrofor Syst 60:131–136

Li G, Jiang G, Li Y, Liu M, Peng Y, Li L, Han X (2007) A new approach to the fight against desertification in Inner Mongolia. Environ Conserv 34:95–97. https://doi.org/10.1017/S0376892907003864

Liu Y, Xue Y (2020) Expansion of the Sahara Desert and shrinking of frozen land of the Arctic. Sci Rep 10(1):1–9

Lu F, Hu H, Sun W, Zhu J, Liu G, Zhou W, Zhang Q, Shi P, Liu X, Wu X, Zhang L, Wei X, Dai L, Zhang K, Sun Y, Xue S, Zhang W, Xiong D, Deng L, Liu B, Zhou L, Zhang C, Zheng X, Cao J, Huang Y, He N, Zhou G, Bai Y, Xie Z, Tang Z, Wu B, Fang J, Liu G, Yu G (2018) Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. Proc Natl Acad Sci 115:4039–4044. https://doi.org/10.1073/pnas.1700294115

Maestre FT, Salguero-Gomez R, Quero JL (2012) It is getting hotter in here: determining and projecting the impacts of global environmental change on drylands. Philos Trans R Soc B 367: 3062–3075

Mahowald NM, Kloster S, Engelstaedter S, Moore JK, Mukhopadhyay S, McConnell JR, Albani S, Doney SC, Bhattacharya A, Curran MAJ, Flanner MG, Hoffman FM, Lawrence DM, Lindsay K, Mayewski PA, Neff J, Rothenberg D, Thomas E, Thornton PE, Zender CS (2010) Observed 20th century desert dust variability: impact on climate and biogeochemistry. Atmos Chem Phys 10:10875–10893. https://doi.org/10.5194/acp-10-10875-2010

Mbow C (2017) The great green wall in the Sahel. Oxford Res Encycl. https://doi.org/10.1093/acrefore/9780190228620.013.559

Melesse A, Steingass H, Schollenberger M, Holstein J, Rodehutscord M (2019) Nutrient compositions and in vitro methane production profiles of leaves and whole pods of twelve tropical multipurpose tree species cultivated in Ethiopia. Agrofor Syst 93:135–147

Mengistu T, Teketay D, Hulten H, Yemshaw Y (2005) The role of enclosures in the recovery of woody vegetation in degraded dryland hillsides of central and northern Ethiopia. J Arid Environ 60:259–281

Menz MHM, Dixon KW, Hobbs RJ (2013) Hurdles and opportunities for landscape-scale restoration. Science 339:526–527. https://doi.org/10.1126/science.1228334

Michels K, Lamers JPA, Buerkert A (1998) Effects of windbreak species and mulching on wind erosion and millet yield in the Sahel. Exp Agric 34:449–464

Middleton NJ (2017) Desert dust hazards: a global review. Aeolian Res 24:53–63. https://doi.org/10.1016/J.AEOLIA.2016.12.001

Middleton N, Kang U (2017) Sand and dust storms: impact mitigation. Sustain For 9(6):1053. https://doi.org/10.3390/su9061053

Mirzabaev A, Nkonya E, Goedecke J, Johnson T, Anderson W (2016) Global drivers of land degradation and improvement. In: Nkonya E, Mirzabaev A, von Braun J (eds) Economics of land degradation and improvement—a global assessment for sustainable development. Springer, Cham, pp 117–165

Mirzabaev A, Wu J, Evans J, García-Oliva F, Hussein IAG, Iqbal MH, Kimutai J, Knowles T, Meza F, Nedjraoui D, Tena F, Türkeş M, Vázquez RJ, Weltz M (2019) Desertification. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva

Mirzabaev A, Wu J, Evans J, Garcia-Oliva F, Hussein IAG, Iqbal MH, Kimutai J, Knowles T, Meza F, Nedjroaoui D et al (2021) Desertification. PhilPapers. Available https://philpapers.org/rec/NGCD

Mirzabaev A, Sacande M, Motlagh F, Shyrokaya A, Martucci A (2022) Economic efficiency and targeting of the African Great Green Wall. Nat Sustainab 5:8. https://doi.org/10.1038/s41893-021-00801-8

Mitchell DJ, Fullen MA, Trueman IC, Fearnehough W (1998) Sustainability of reclaimed desertified land in Ningxia, China. J Arid Environ 39:239–251

Mori I, Nishikawa M, Tanimura T, Quan H (2003) Change in size distribution and chemical composition of kosa (Asian dust) aerosol during long-range transport. Atmos Environ 37(30): 4253–4263

Ndayambaje J, Mohren G (2011) Fuelwood demand and supply in Rwanda and the role of agroforestry. Agrofor Syst 83:303–320

Nyoka BI, Mngomba SA, Akinnifesi FK, Ajayi OC, Sileshi G, Jamnadass R (2011) Agroforestry tree seed production and supply systems in Malawi. Small-Scale For 10:419–434

O'Connor D, Ford J (2014) Increasing the effectiveness of the "Great Green Wall" as an adaptation to the effects of climate change and desertification in the Sahel. Sustain For 6:7142–7154. https://doi.org/10.3390/su6107142

Onyewotu LOZ, Stigter CJ, Oladipo EO, Owonubi JJ (2004) Air movement and its consequences around a multiple shelterbelt system under advective conditions in semi-arid Northern Nigeria. Theor Appl Climatol 79:255–262

Parungo F, Li Z, Li X, Yang D, Harris J (1994) Gobi dust storms and the great green wall. Geophys Res Lett 21:999–1002. https://doi.org/10.1029/94GL00879

Prăvălie R (2016) Drylands extent and environmental issues. A global approach. Earth-Sci Rev 161: 259–278. https://doi.org/10.1016/J.EARSCIREV.2016.08.003

Pricope NG, Husak G, Lopez-Carr D, Funk C, Michaelsen J (2013) The climate-population nexus in the East African Horn: Emerging degradation trends in rangeland and pastoral livelihood zones. Glob Environ Chang 23:1525–1541

Qor-el-aine A, Béres A, Géczi G (2022) Dust storm simulation over the Sahara Desert (Moroccan and Mauritanian regions) using HYSPLIT. Atmos Sci Lett 23:e1076. https://doi.org/10.1002/asl.1076

Querol X, Tobías A, Pérez N, Karanasiou A, Amato F, Stafoggia M, García-Pando CP, Ginoux P, Forastiere F, Gumy S, Mudu P, Alastuey A (2019) Monitoring the impact of desert dust outbreaks for air quality for health studies. Environ Int 130:104867. https://doi.org/10.1016/j.envint.2019.05.061

Rodríguez S, Alastuey A, Alonso-Pérez S, Querol X, Cuevas E, Abreu-Afonso J, Viana M, Perez N, Pandolfi M, de la Rosa J (2011) Transport of desert dust mixed with North African industrial pollutants in the subtropical Saharan air layer. Atmos Chem Phys 11:6663–6685. https://doi.org/10.5194/acp-11-6663-2011

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Jones JW (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci U S A 111(9):3268–3273. https://doi.org/10.1073/pnas.1222463110

Sacande M (2018) Action against desertification, land restoration. Rome, Italy. Retrieved from http://www.fao.org/3/i9144en/I9144EN.pdf

Sadeghimoghaddam A, Khankeh H, Norozi M, Fateh S, Farrokhi M (2021) Investigating the effects of dust storms on morbidity and mortality due to cardiovascular and respiratory diseases: a systematic review. J Educ Health Promot 31:191. https://doi.org/10.4103/jehp.jehp_1272_20

Sanz MJ, de Vente J, Chotte JL, Bernoux M, Kust G, Ruiz I, Almagro JM, Alloza JA, Vallejo R, Castillo V, Hebel A, Akhtar-Schuster M (2017) Sustainable land management contribution to successful land-based climate change adaptation and mitigation. A report of the science-policy interface. United Nations Convention to Combat Desertification (UNCCD), Bonn

Sayre R, Martin M, Karagulle D, Frye C, Breyer S, Wright D, Butler K, Van Graafeiland K, Boucher T, McGowan J, Touval J, Wolff NH, Sotomayor L, Game ET, Possingham H (2020) World terrestrial ecosystems. In: Goldstein MI, DellaSala DA (eds) Encyclopedia of the world's biomes. Elsevier, Oxford, pp 31–34. https://doi.org/10.1016/B978-0-12-409548-9.12474-1

Sherwood S, Fu Q (2014) A drier future? Science 343:737–739. https://doi.org/10.1126/science.1247620

Sileshi GW (2016) The magnitude and spatial extent of influence of *Faidherbia albida* trees on soil properties and primary productivity in drylands. J Arid Environ 132:1–14. https://doi.org/10.1016/j.jaridenv.2016.03.002

Sileshi G, Akinnifesi FK, Ajayi OC, Chakeredza S, Kaonga M, Matakala P (2007) Contribution of agroforestry to ecosystem services in the miombo eco-region of eastern and southern African. Afr J Environ Sci Technol 1(4):68–80

Sileshi GW, Arshad MA, Konaté S, Nkunika PO (2010) Termite-induced heterogeneity in African savanna vegetation: mechanisms and patterns. J Veg Sci 21:923–937

Singh J, Ashfaq M, Skinner CB, Anderson WB, Mishra V, Singh D (2022) Enhanced risk of concurrent regional droughts with increased ENSO variability and warming. Nat Clim Chang 12:163–170. https://doi.org/10.1038/s41558-021-01276-3

Sörensen L (2007) A special analysis approach to the global delineation of drylands areas of relevance to the CBD Programme of work on drylands and subhumid lands. UNEP-WCMC. https://www.unepwcmc.org/system/dataset_file_fields/files/000/000/323/original/dryland_report_final_HR.pdf?1439378321

Speranza CI, Scholz I (2013) Special issue "adaptation to climate change: analysing capacities in Africa". Reg Environ Chang 13:471–475

Stefanski R, Sivakumar MVK (2009) Impacts of sand and dust storms on agriculture and potential agricultural applications of a SDSWS. IOP Conf Ser 7(1):012016. https://doi.org/10.1088/1755-1307/7/1/012016

Sterk G, Stoorvogel JJ (2020) Desertification–scientific versus political realities. Landscape 9:156. https://doi.org/10.3390/land9060156

Takemura T, Uno I, Nakajima T, Higurashi A, Sano I (2002) Modeling study of long-range transport of Asian dust and anthropogenic aerosols from East Asia. Geophys Res Lett 29(24): 2158. https://doi.org/10.1029/2002GL016251

Tamou C, Ripoll-Bosch R, de Boer IJMM, Oosting SJ (2018) Pastoralists in a changing environment: the competition for grazing land in and around the W Biosphere Reserve, Benin Republic. Ambio 47:340–354. https://doi.org/10.1007/s13280-017-0942-6

Tan M, Li X (2015) Does the Green Great Wall effectively decrease dust storm intensity in China? A study based on NOAA NDVI and weather station data. Land Use Policy 43:42–47. https://doi.org/10.1016/j.landusepol.2014.10.017

Thomas N, Nigam S (2018) Twentieth-century climate change over Africa: seasonal 2 hydroclimate trends and Sahara desert expansion. J Clim 31(9):3349–3370. https://doi.org/10.1175/JCLI-D-17-0187.1

Tobias A, Stafoggia M (2020) Modeling desert dust exposures in epidemiologic short-term health effects studies. Epidemiology 31:788–795. https://doi.org/10.1097/EDE.0000000000001255

Trabucco A, Zomer R (2019) Global aridity index and potential evapotranspiration (ET0) Climate Database v2. https://doi.org/10.6084/m9.figshare.7504448.v3

UNCCD (2007). www.unccd.entico.com/english/glossary.ht

UNCCD (2019) The great green wall initiative. United Nations Convention to Combat Desertification. United Nations, New York

UNCCD (2020) The great green wall implementation status and way ahead to 2030. https://catalogue.unccd.int/1551_GGW_Report_ENG_Final_040920.pdf

UNCCD (2022) The great green wall initiative. In: United Nations convention to combat desertification (UNCCD). The great green wall initiative. https://www.unccd.int/actions/great-green-wall-initiative. Accessed 7 Mar 2022

van der Esch S, Brink BT, Stehfest E, Bakkenes M, Sewell A, Bouwman A, Meijer J, van den Berg M (2017) Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: scenarios for the UNCCD Global Land Outlook. UNCCD Global Land Outlook

Veste M, Gao J, Sun B, Breckle SW (2006) The green great wall – combating desertification in China. Geogr Rundschau Int Ed 2(3):14–20

Votsis A, Barnaba F, Basart S, Tomaso ED, Formenti P, Lindfors A, Mona L, Rautio T, Wang Y, Hidalgo EW (2020) Operational risks of sand and dust storms in aviation and solar energy: the DustClim approach. FMI's Clim Bull Res Lett 2020:1. https://doi.org/10.35614/ISSN-2341-6408-IK-2020-02-RL

Votsis A, Basart S, Barnaba F, Di Tomaso E, Lindfors A, Mona L, Mytilinaios M, Formenti P, Rautio T, Wang Y, Werner E, Pérez García-Pando C (2021) Addressing the impacts of sand and dust storms in North Africa, the Middle East and Europe for air quality, aviation and solar energy: the DustClim approach to climate services. EGU General Assembly 2021, EGU21-12819. https://doi.org/10.5194/egusphere-egu21-12819

Wairore JN, Mureithi SM, Wasonga OV, Nyberg G (2016) Benefits derived from rehabilitating a degraded semi-arid rangeland in private enclosures in west pokot county, Kenya. Land Degrad Dev 27:532–541

Wang XM, Zhang CX, Hasi E, Dong ZB (2010) Has the three norths forest shelterbelt program solved the desertification and dust storm problems in arid and semiarid China? J Arid Environ 74:13–22

Wang F, Pan X, Wang D, Shen C, Lu Q (2013) Combating desertification in China: past, present and future. Land Use Policy 31:311–313

Wang S, Fu B, Piao S, Lü Y, Ciais P, Feng X, Wang Y (2016) Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat Geosci 9:38–41. https://doi.org/10.1038/ngeo2602

Wiesmeier M, Munro S, Barthold F, Steffens M, Schad P, Kögel-Knabner I (2015) Carbon storage capacity of semi-arid grassland soils and sequestration potentials in northern China. Glob Chang Biol 21(10):3836–3845. https://doi.org/10.1111/gcb.12957

Wilske B, Lu L, Wei L, Chen S, Zha T, Liu C, Xu W, Noormets A, Huang J, Wei Y, Chen J, Zhang Z, Ni J, Sun G, Guo K, McNulty S, John R, Han X, Lin G, Chen J (2009) Poplar plantation has the potential to alter the water balance in semiarid Inner Mongolia. J Environ Manag 90:2762–2770. https://doi.org/10.1016/j.jenvman.2009.03.004

World Bank (2018) Groundswell: preparing for internal climate migration. World Bank, Washington

World Bank (2019) Sand and dust storms in the middle east and north Africa region—sources, costs, and solutions. World Bank, Washington

Xu W, Xiao Y, Zhang J, Yang W, Zhang L, Hull V, Wang Z, Zheng H, Liu J, Polasky S, Jiang L, Xiao Y, Shi X, Rao E, Lu F, Wang X, Daily GC, Ouyang Z (2017) Strengthening protected areas for biodiversity and ecosystem services in China. Proc Natl Acad Sci 114:1601–1606. https://doi.org/10.1073/pnas.1620503114

Yang H, Li G, Wang Z, Jia R, Liu L, Chen Y, Wei Y, Gao Y, Li G (2014) Carbon sequestration capacity of shifting sand dune after establishing new vegetation in the Tengger Desert, northern China. Sci Total Environ 478:1–11. https://doi.org/10.1016/J.SCITOTENV.2014.01.063

Zdruli P, Pagliai M, Kapur S, Cano AF (eds) (2010) Land degradation and desertification: assessment, mitigation and remediation. Springer, Dordrecht

Zhang X, Zhao L, Tong D, Wu G, Dan M, Teng B (2016) A systematic review of global desert dust and associated human health effects. Atmos 7:158. https://doi.org/10.3390/atmos7120158

Zhao T, Dai A (2015) The Magnitude and causes of global drought changes in the twenty first century under a low–moderate emissions scenario. J Clim 28:4490–4512. https://doi.org/10.1175/JCLI-D-14-00363.1

Zheng YR, Xie ZX, Robert C, Jiang HL, Shimizu H (2006) Did climate drive ecosystem change and induce desertification in Otindag sandy land, China over the past 40 years? J Arid Environ 64:523–541

Zheng X, Zhu J, Xing Z (2016) Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China. Agric Syst 143:49–60. https://doi.org/10.1016/j.agsy.2015.12.008

Chapter 7
Silvopastoral Systems on Degraded Lands for Soil Carbon Sequestration and Climate Change Mitigation

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Abstract Land degradation is a deleterious process affecting the biophysical environment of soils and reduces the natural or agricultural capacity of soil to support plant growth and net primary productivity, promoting a broad-scale, net loss of soil organic carbon (SOC) to the atmosphere through increased CO_2 emissions from soil to the atmosphere and lower carbon storage in aboveground biomass. Consequently, land degradation represents the main threat to food security worldwide, especially in Africa and Asia. At present, about 40% of the global land area is affected by land degradation, 9% being severe. Silvopastoral systems, which are planned combinations of trees, forage-herbs and livestock, constitute one of the main forms of agroforestry systems currently covering about 28% of the global area of these. This chapter demonstrates that silvopastoral systems represent the principal land uses for land conservation-reclamation and reducing-offset C emissions from soil by promoting the formation of soil organic matter and increasing SOC named carbon sequestration ($CO_2 \rightarrow SOC$), enhancing soil quality and improving ecosystem

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services like water and nutrient cycling and livestock well-being. In this review, we have identified 25 major mechanisms responsible for soil organic matter, soil quality, and carbon emission offset including: 12 individual functions for the woody (6), herbaceous (3) and animal (3) components, in addition to 13 symbiotic drivers (8 mutualistic and 5 tripartite interactions), whereas the reported values of C fixation in silvopastoral systems are 1–5 Mg C ha^{-1} year^{-1} and $CO_2 \rightarrow$SOC range from 1.8 to 7.5 Mg C ha^{-1} year^{-1}, demonstrating the potential of silvopastoral systems to ameliorate or reverse land degradation. However, the scientific reports related to silvopastoral systems and their benefits are mainly concentrated in certain global zones (e.g. developed countries), which suggests that this may be potentially useful in addressing land degradation in other priority regions such as Asia and Africa.

Keywords Sustainable agriculture · Soil reclamation · Soil quality · Agroforestry · Silvopastoral systems · Degraded lands · Carbon sequestration · Climate change mitigation · Carbon emissions

7.1 Introduction

Humans have caused a continual transformation of the planet's surface since ancient times ranging from 7500 to 10,000 years ago (Dotterweich 2013), inducing deleterious changes on the structural and functional patterns of terrestrial ecosystems (Ludwig 2005), which comprises soil, near surface air, vegetation, other associated biota and water, collectively named '*land*' (Henry et al. 2019).

The cumulative net land modifications include: the creation and expansion of urban centres and massive deforestation caused by the expansion of the agriculture frontier both subsistence and intensive agriculture, and/or over-exploitation of native species, which are collectively termed as 'land-use changes' (De Fries et al. 2004). Although land-use changes can vary greatly both spatially and temporarily, they frequently involve the vicious cycle of 'extractive acquisition of natural resources for immediate human use', a phenomenon designed as 'land degradation' (land degradation (Vitousek 1997).

According to Mohamed et al. (2019), land degradation is defined as a '*set of processes that lead to changes in the values of the biophysical environment and land characteristics to be deleterious*'. Land degradation is a multi-factorial and interdependent phenomenon, comprising a myriad of detrimental physical–chemical–biological processes (simultaneous or successive) that are mediated by natural or human induced factors (Fig. 7.1), which impact the ability of an ecosystem to support net primary production (e.g. annual C absorption by living plants), which is a reason why a decreasing NPP is an indicator of land degradation (Barbier and Hochard 2018).

According to FAO (2007), major human pressures or drivers that affect land degradation include demands from: agriculture, nutrient mining, waste disposal, population growth, intensive cultivation, over grazing and excessive irrigation.

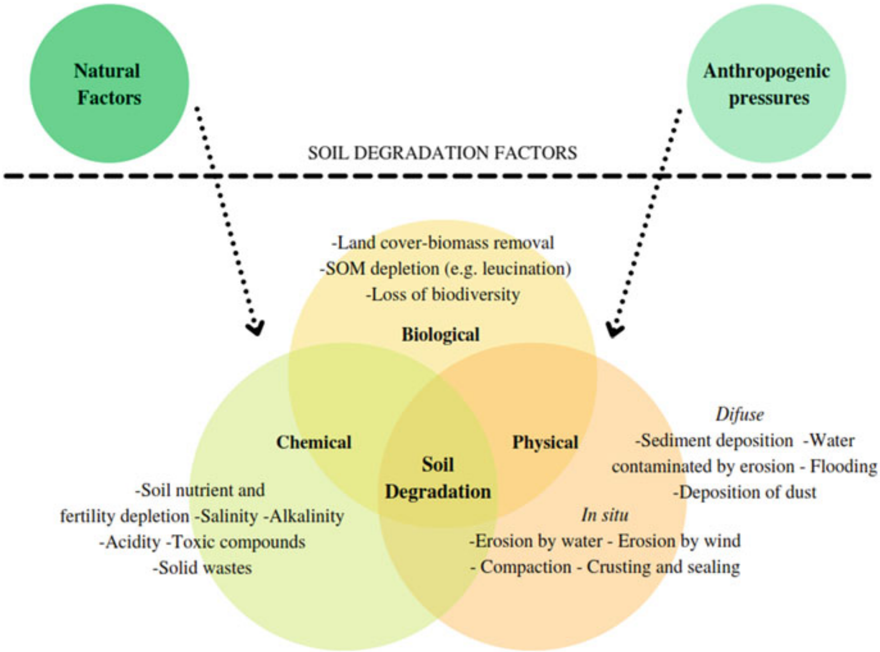

Fig. 7.1 An overview of main soil degradation processes—land degradation, as natural and/or anthropogenic phenomenon, divided into physical, chemical or biological, showing interactivity-simultaneity-interdependence, causing a net effect leading to ecosystem modification to destruction gradients (after Olsson et al. 2019)

Examples of historic land-use change–land degradation include: deforestation, which is responsible for about 77% of global C losses (Houghton and Nassikas 2018); the conversion of freshwater wetlands (about 1% earth's surface) into for agricultural purposes (Dixon et al. 2016); a worldwide utilization (direct or indirect) of one-third of the land surface for livestock production that also promotes detrimental shifts of vegetational patterns via overgrazing and erosion (Giraldo et al. 2011; Kuzyakov et al. 2016) and salinization that currently affects 13% of agricultural area through various processes (e.g. deficient water management for crop production in arid and semi-arid zones), but is expanding at a rate of 1.6 M ha year^{-1} (Mohamed et al. 2019).

By definition, silvopastoral systems refer to '*multifunctional systems that combine herbage*, *shrub and tree layers with grazing animals in a single site*' (Sales-Baptista and Ferraz-de-Oliveira 2021), are environmentally resilient land management systems recognized to promote land productivity, besides ecosystem-climatic and social benefits, including: C fixation in vegetational biomass (tree and herbaceous), and SOC, compared to open and treeless areas (Aryal et al. 2019; Beer et al. 2003), and increasing the carbon storage potential of grasslands (Jose and Bardhan 2012; Feliciano et al. 2018), ecosystems services (e.g. water-nutrient cycling).

For improving degraded lands, silvopastoral systems can successfully be implemented because they can provide multiple benefits and ecosystem services. Pedogenesis, productive outcomes (e.g. timber, animal products), climatic benefits (e.g. climate and air regulation), aesthetic, educational and democratization values and protection of habitats (particularly encouraging endemic) (Maathai 2012; Sales-Baptista and Ferraz-de-Oliveira 2021), are economically feasible (Sharrow et al. 2015). Currently, silvopastoral systems cover worldwide about 450 M ha (28% of the total agroforestry systems) (Nair 2012), having multiple possible combinations of components and arrangements, generating great adaptability to conditions and needs (Sales-Baptista and Ferraz-de-Oliveira 2021).

Silvopastoral systems are widespread in tropical and subtropical regions of Africa and Asia involving extensive open and control grazing by animals under natural stands of trees and shrubs (Soni et al. 2016; Dagar et al. 2020a; Nair et al. 2021); for example, the parklands of sub-Saharan Africa (Dagar et al. 2020), and the silvopastoral systems of arid and semiarid lands of the Indian subcontinent (Dagar and Gupta 2020). Silvopastoral systems in Africa represent the land-use systems in which woody perennials are combined with silvopastoral systems including cut-and-carry (protein bank) system, live fences and fodder foliage; browsing and grazing being the main components of these practices (Dagar et al. 2020; Nair et al. 2021).

Agrosilvopastoral agroforestry practices in Southeast Asia include trees on rangelands, protein banks and plantation crops with pastures and animals (Shin et al. 2020). The aim of this chapter is to discuss processes and effects of land degradation, the silvopastoral systems for degraded lands and bio-physical mechanisms for carbon sequestration in silvopastoral systems.

7.2 Main Processes and Effects of Land Degradation

The mechanisms responsible for land degradation are diverse (mostly mediated by human activities), and result from a wide range of multi-temporal events that include short-term storms (minutes), decade length processes of gully formation to century long extractions of soil nutrients (Coppus and Imeson 2002; Johnson and Lewis 2007), as discussed in the broad overview of all processes causing land degradation and their implications by Olsson et al. (2019) (Table 7.1).

Additional drivers that influence land degradation have been detected and include land tenure changes and variation in crop prices, both of which exert shifts of land-use change or management that potentially cause land degradation (Millennium Ecosystem Assessment 2005).

Among the consequences of land degradation are: (1) ecosystem fragmentation patterns, resulting on a decline of biodiversity through habitat loss and connectivity between habitats; (2) soil and water degradation that may extend beyond their natural boundaries (e.g. marine and freshwater systems) (Sala 2000; Stocking and Murnaghan 2001); (3) weakened regulation of ecosystem services/terrestrial cycles such as nutrients and C (Vitousek 1997; Gashaw et al. 2014; Olsson et al. 2019);

Table 7.1 Principal mechanisms of land degradation and their main implications (after Olsson et al. 2019)

Processes	Probable causes	Effects
[1] Organic matter decay(S)	Conventional/intensive cultivation (monocultures), tillage, removal of groundcover/vegetation clearing, overgrazing, deforestation. Drainage of waterlogged soils Influenced by most of land degradation	– Net C release – Warming enhances soil respiration – Decrease of litter quality (greater C:N ratio) – Variations on water cycle (e.g. logging) – Changes on fire events
[2] Compaction (S)	Land-use change, conventional/intensive cultivation (monocultures), over-utilization of machinery, intensive grazing	– Reducing actual SOC and potential SOM intake – Limiting root developed-, air supply and ultimately plant growth – N_2O emissions
[3] Biological soil crust removal (S−B)	Land-use change Overgrazing—excessive trampling	– Modification of rainfall patterns – Albedo increase – Radiative cooling via dust release – Variation on fire regimes
[4] Soil micro–meso faunal shifts (S−B)	Modified fire regimes, N content variations (e.g. N deposition), over-fertilization, pesticide pollution, alteration of vegetational resources	– Habitat losses
[5] Nutrient depletion(S)	Soil nutritional status decline/harvested nutrients (e.g. conventional/intensive cultivation monocultures)	– Net C losses via alterations of SOC reservoir – Possible changes in land uses (e.g. cropland) – Possible overfertilization
[6] Acidification and/or overfertilization(S)	Overutilization of N-based fertilizers/ cation depletion/acid rain	– N_2O release – Release of C in inorganic forms
[7] Pollution(S−B)	Use of herbicides/pesticides	– Potential increase of pest and weed resistance—incidence
[8] Flooding (W)	Expansion of impervious surface and infrastructure, land clearing	– CH_4 release – N_2O emissions – Sea level increase – Rising rainfall intensity – Shifts of vegetational patterns
[9] Waterlogging (W)	Poor drainage practices/deforestation	– CH_4 release – Water balance alterations – Shifts of vegetational patterns
[10] Salinization (S−W)	Poor drainage practices	– High sulfate loads – Reduction on CH_4 emissions

(continued)

Table 7.1 (continued)

Processes	Probable causes	Effects
		– Increment of sea level – Water balance shifts
[11] Sodification (S–W)	Deficient water management	– Net C losses via breakdown of stable aggregates releasing occluded SOC – Water balance shifts – Albedo increase
[12] Water erosion(S)	Conventional/intensive cultivation (monocultures), tillage, removal of groundcover/vegetation clearing, overgrazing, deforestation, fire regime shifts, deficient designed roads and paths	– Net C release – Albedo increase
[13] Wind erosion(S)	Conventional/intensive cultivation (monocultures), tillage, removal of groundcover/vegetation clearing, overgrazing, deforestation, fire regime shifts	– Changing wind/drought patterns – Radiative cooling – Ocean fertilization
[14] Coastal erosion(S-W)	Detainment of sediments, coastal agriculture, mangrove forests removal, subsidence	– Sea level rise – Increase of frequency and intensity of storms – Release of stable/buried/ old C pools
[15] Increased burning (S–B)	Changing precipitation regimes	– Warming increase – Net C (e.g. CO_2, CO, CH_4) and N_2O release – Albedo increase – Possible changes on soil nutrient status – Long-term drop of NPP
[16] Invasions(B)	Deliberated or accidental introduction of exotic species	– Habitat shifts/decline for native or pre-existent species
[17] Woody encroachment (B)	Invasive processes, shift of fire regimes or fire suppression	– Albedo decrease – Net C storage – CO_2 rise

[1, 2…17] Process number, [S/W/B] Land component in which a determined land degradation process acts, where: *S* soil, *W* water, *B* biota

(4) enhanced emission of greenhouse gases (e.g. atmospheric compounds that able to absorb–emit infrared radiation, forcing thermal atmospheric alterations (e.g. carbon dioxide [CO_2], methane [CH_4] and nitrous oxide [N_2O]), which is strongly associated with climate change and dates back from at least 3000 years ago from the origins of land-use change) (Ellis et al. 2013); (5) detrimental changes in soil productivity, biological productivity, ecological integrity (Stocking and Murnaghan 2000) and (6) habitat destruction, loss of biodiversity (including extinction of vulnerable species flora and fauna), changes in human population (both size and distribution), diffuse events of pollution (e.g. atmospheric deposition) and other off-site impacts (FAO 2007) (Table 7.1, Fig. 7.1).

From a social point of view, land degradation exerts effects on both cultural and economic spheres, frequently modifying the dynamics of market and technology, and demographic patterns.

7.2.1 Climate Change and Land Degradation

Although there is considerable literature regarding land degradation and climate change, less is known about their possible linkages and synergism as deleterious forces (Webb et al. 2017). In this respect, it is considered that land degradation and climate change reciprocally accelerate each other, but actual few studies supporting the premise [land degradation → climate change] have been reported (Stocking and Murnaghan 2000). On the contrary, more information is available regarding [climate change → land degradation], such as permafrost thawing (Schuur et al. 2015; Batir et al. 2017), ground subsidence (Keogh and Törnqvist 2019) and tree mortality (Allen et al. 2010), since climate change could be considered a mechanism and a driver of land degradation at the same time.

According to Lin et al. (2017), there are three main factors associated with climate change that can escalate land degradation processes, including periodic variations of temperature, precipitation and wind, which exert modifications on the distribution, intensity and periodicity of extreme events. However, despite the pronounced and visible adverse effects of climate change, it has been stated that a positive aspect of climate change could be the expansion of cultivable areas in northern latitudes of about 560 Mha (Zabel et al. 2014).

7.2.1.1 Relationship Land Degradation, SOC, Soil Quality and Greenhouse Gases Emissions

The following section establishes the main role of SOC in relation to land degradation processes, soil functionality and its contribution as a principal threat associated with climate change.

Relevance of Soil Degradation in Land Degradation

Land degradation is widely linked to soil disruptions, where about 15 major processes identified by Olsson et al. (2019) are precursors of land degradation and directly related to soil (7 utterly) (Table 7.1).

Therefore, soil degradation has been defined by FAO (2007) as: 'change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Degraded soils have a health status such, that they no longer provide the normal goods and services for the soil in its ecosystem'. The soil is therefore a principal focal and/or starting point of land degradation.

Soil degradation occurs as: (1) erosion or displacement of soil materials via superficial water flow (comprising 56% of global soil degradation), via wind (28%), both causing losses and deformations from topsoil to subsoil (e.g. gullies) and (2) alterations within soil matrix via (a) chemical degradation which reduces the fertility status, causes pollution and/or salinization–sodification (12% of global soil degradation), and also by the following the land degradation processes: acidification, salinization, nutrient depletion (e.g. reduction of exchange capacity, increase of Mn or Al toxicity, Ca or Mg deficiencies, leaching of available N forms such as NO^{-3}) and (b) physical degradation, linked to the land degradation processes: compaction, crusting, reduced water infiltration, increased surface runoff, greater soil temperature fluctuations and flooding (4% of global soil degradation) (Lal 2015).

The Role of SOC in Land Degradation

Soil organic matter (SOM) is formed by biomass production, litterfall and root exudates, and biological activity is defined as 'The heterogeneous mixture of organic compounds encompassing molecules released from both, living plant and microbial cells (e.g. extracellular enzymes, surface-active proteins, chelating compounds) and complex plant, microbial and animal residues in various stages of alteration due to biotic and abiotic processes' (Baldock and Nelson 2000). SOM contains about 56–60% of soil organic carbon (SOC) (Heaton et al. 2016).

Thus, SOM is a broad inclusive concept of key relevance because it involves a myriad of ecological processes, grouped in: (1) improvement of soil fertility status through the release of different nutrients such as N, P (Odhiambo et al. 2001; Akinnifesi et al. 2007), and Mg, K, Ca (Haynes and Mokolobate 2001), (2) regulation of hydrological cycle (Alavalapati et al. 2004), (3) protection of soil against erosive agents (e.g. wind and water) (Alavalapati et al. 2004), (4) $CO_2 \rightarrow$SOC, (5) increasing soil-aboveground agro-biodiversity that also serve as biological corridors for other species (Rigueiro-Rodríguez et al. 2008) and (6) reduction of necessary input requirements to the ecosystem (e.g. El-Ramady et al. 2014).

Since land degradation potentially modifies the environmental drivers affecting soil formation including structural internal organization, temperature, moisture, climate, plant/animal presence, soluble/exchangeable cations, pH and litter input (Sollins et al. 1996), soil degradation thereby exacerbates SOC losses (e.g. SOC destabilization) and limiting-inhibiting the formation of new SOC (Lal 2015).

The mechanisms of SOC destabilization are described by Sollins et al. (1996) and refer to the overall processes by which: (1) SOC became less resistant to degradation (e.g. recalcitrance) by depolymerization processes involving changes in enzymatic production mediated by an enhancement of microbial activity, which is usually expected to be caused by changes in the quality and quantity of detritus/substrate (e.g. degradation rates are related to litter chemistry, their C:N ratio, and lignin/tannin contents), (2) increased desorption of C in organo-mineral forms, as a consequence of microbial activity-enzymatic production leading the formation of more biodegradable SOC forms (dissolved organic carbon) and/or (3) the increase of microbial accessibility to protected or occluded SOC, via physical breakdown of detritus and soil aggregates (e.g. tillage), increasing the activity of soil fauna and microbial-extracellular enzymes, promoting the solubilization of binding agents. However, aggregate stability varies according to clay mineralogy and presence of Na^+, which deflocculates clays.

7.2.1.2 Land Degradation and Soil Quality

Land degradation—soil degradation may induce a decline in specific soil properties-processes, affecting its capacity to sustain vegetation and provide ecosystem services, both of which are considered in the term '*soil quality*' (SQ) (Arshad and Martin 2002; Karlen et al. 2003; UNEP 2016).

According to the Soil Science Society of America, SQ is defined as: 'The fitness of a specific soil-type, to function within its capacity, and within natural or managed ecosystem boundaries, to sustain animal and plant productivity, maintain or enhance water and air quality, and support human health and habitation' (Arshad and Martin 2002). The SQ thus represents the *status quo* of a particular soil with respect to its potential at a given moment (UNEP 2016).

The SQ is measured by identifying comparative and space-time sensitive soil properties among different types of management, under similar pedo-climatic conditions. These are accordingly named soil quality indicators (SI_{ND}) which express different aspects of soil functionality (Arshad and Martin 2002; Karlen et al. 2003). Additionally, the SQ is also a useful tool to diagnose and monitor land degradation – soil degradation.

7.2.1.3 Land Degradation and Greenhouse Gases Emissions

Diverse land degradation processes and land-use change (e.g. deforestation) proceed from net SOC destabilization processes, thereby accelerating the biological active emission of CO_2 from soil, contributing to climate change (Mohamed et al. 2019; Olsson et al. 2019). In addition, there are a complex set of indirect side effects during SOC destabilization caused by diverse land degradation processes and land-use change (e.g. tillage) that further intensify SOC decline in soil and CO_2 release to the atmosphere.

For instance, during the disruption of soil structure (or disaggregation), the amount of arbuscular mycorrhizal fungi is reduced (Wall et al. 2004), affecting the potential formation of stable forms (resistant to degradation) of SOM such as glomalin, while SOC translocation via bioturbation is also limited due to a decline in earthworm populations, and a reduction of vertical movement of dissolved forms of SOC via diminution of water infiltration to soil and soil water-holding capacity (Wall et al. 2004; Wang et al. 2017). To date, during the period 2007–2016, C emissions from land-use change were about 1.3 ± 0.7 Pg $year^{-1}$ (Le Quéré et al. 2018), while IPCC (2006) reports that 47% of CO_2 emissions originate from soil.

Conversely, the N_2O emissions from soil are mediated by soil microbial activity which is affected by soil disruptions-management practices and climate conditions, while CH_4 emissions are primarily proportional to the amount of SOC-waterlogging, both of which are strongly correlated to land degradation—land-use change—soil degradation (Dou et al. 2016; Oertel et al. 2016; Olsson et al. 2019). Indeed, according to IPCC (2006), about 35% of global CO_2, 47% of CH_4 and 53% of N_2O emissions are generated from soil.

In terms of vulnerability, dry lands are probably the most endangered ecosystems since their limited capacity to provide food, commodities and environmental services. Consequently, the most susceptible continents to land degradation–land-use change are Africa and Asia, since their territories are comprised of dry lands (66% and 40%, respectively, together totalling 3.6 billion ha). In fact, it is estimated that 66% and 71% of Africa and Asia territories, respectively, are already affected by desertification (e.g. land degradation–land-use change in dry lands) (Soni et al. 2016).

Asia is the largest continent in the world, covering about 44 million km^2 (29% of global area), which supports the demands of about 60% of global human population (70% of this percentage living in rural zones). It is estimated that 35% of arable land and 39% of total population in Asia (1.3 billion people) are under significant desertification (land degradation). The major historic and current facts resulting in land degradation–land-use change, including high population growth leading to an increment of land pressure (e.g. decline of natural resources functions such as soil and water and ecosystem depletion such forests and grasslands), rising massive CO_2 evolution via respiration, promoting climate change (Ma and Ju 2007). At a regional scale, in: (1) central Asia (e.g. China, Mongolia), where desertification represents the major land degradation–land-use change risk due to the rugged dry land countries and high demographic concentration; for example, it is estimated that about 27.5% of Chinese territory and up to 90% of Mongolia's surface are affected by desertification processes, respectively and (2) west Asia (e.g. Iran, Saudi Arabia), the particular Mediterranean climate associated with the highest global population growth rates (2.4%), changes on consumption habits and life styles, generates high demands on natural resources commodities, resulting on different land degradation processes, such as both wind and water erosion, salinization and low productivity due to permanent grazing processes in marginal areas and rangelands, besides the constant expansion of agricultural area (at the expense of natural ecosystems), commonly by using unsuitable irrigation sources, (3) south Asia (e.g. India), the region with the highest population density in the world, exerting severe land pressure through deforestation, soil erosion, overgrazing and desertification, which in turn leads to massive human displacements, initiating the severe cycle of land degradation–land-use change (Ma and Ju 2007).

Africa which comprises an approximate area of 30.1 million km^2, the status of land degradation–land-use change is critical, representing 65% of the global agricultural areas of the world, affecting near to 485 million people. The principal causes of land degradation–land-use change in Africa include the fragility of dry land-based ecosystems–soils and the cumulative effects of inadequate land management, where among the most remarkable processes are deforestation, shifting cultivation, the more frequent erratic climatic conditions. However, some social aspects such as population growth, expanding refugee settlements due to wars and armed conflicts and insecurity in land tenure, are also land degradation–land-use change dynamic agents of great relevance (Thiombiano and Tourino-Soto 2007). However, apart from social factors, pedo-climatic conditions coupled with temporal variations of land uses/land managements, livestock production and forestry technologies, result on a complex mosaic of present/potential land degradation—land-use change processes—status involved. In this regard, a total of 7 major agro-ecological regions have been identified, including: (1) [desert, arid, semi-arid, dry] (e.g. Algeria, Mali, Nigeria, Sudan), (2) [sub-humid, humid and highlands] (e.g. Congo. Ethiopia). Two types of agricultural practices are predominant: (a) ranges from oasis agricultural systems, nomadism, harvesting and hunting in desert (e.g. Sahara or Karoo) over most limiting soils such as Arenosols or Regosols (WRB 2006)/Inceptisols and Entisols (e.g. orthents) (USDA 2014), to transhumance for livestock production and monoculture (e.g. millet–maize–sorghum–fruit) or integrated systems within arid–semi-arid dry regions; (b) in the case monoculture systems (e.g. tea, root, tuber crops), grasslands, forestry (e.g. cocoa, coffee) and agroforestry systems based on sorghum, maize, root and fruit, placed on soils with a wide range of aptitudes–fertility such as cambisols, regosols, solonetz, arenosols, luvisols, calcisols, gypsisols (WRB 2006) or entisols, to alfisols, gleysols, ultisols, vertisols and mollisol (USDA 2014).

7.3 Silvopastoral Systems

The term agroforestry (agroforestry systems) refers in a broad sense to an intentional-intensive-integrated-interactive associations of trees, plants and/or animal-pastures within a determined space (Gold and Garrett 2009; Nair 2012). Despite the historical origins of agroforestry systems as a subsistence–smallholder and flexible indigenous land management (Nair 2015), nowadays, agroforestry systems are widespread around the globe, covering broad extensions (Table 7.2) and are present across natural–rural–peri-urban–urban gradients, mainly due to their evolution to an economically and social-environmentally profitable 'agro-solution' in local and emergent economies (Pachauri 2012), contributing to the livelihoods of about 900 million people (Cardinael et al. 2018).

The social functionality of agroforestry systems is based on seven fundamental precepts: (1) economic and agricultural diversification, (2) environmental impact mitigation, (3) land and water rehabilitation and restoration, (4) increased food production, (5) sustainable use of marginal or fragile land, (6) natural habitat enhancement and (7) profitability (Thevathasan et al. 2018).

The silvopastoral agroforestry practice ranges from the traditional, extensive animal grazing under woodlots and forests to modernized intensive forms of tree–animal integration, including grazing system and the browsing (tree–fodder) systems

Table 7.2 Global area covered by principal agroforestry systems and tree-based agriculture

System	Land area (Mha)	% of SAF
Alley cropping	700	44
Silvopastoral systems	450	28
Protective SAF (e.g. windbreaks, riparian buffer)	300	19
Multi-strata	100	6
Scattered trees	50	3
Global agroforestry systems	1000–1600[a]	
% of tree-based production and agroforestry systems respect to global agriculture area[b]		7.6–20.3

Source: Nair (2012)
[a] Cardinael et al. (2018)
[b] Nair (2012) and Zomer et al. (2016)

Table 7.3 Major agrosilvopastoral agroforestry practices in southeast Asia (from Shin et al. 2020)

Trees on range-land or pastures	Trees scattered irregularly or arranged according to some systematic pattern	Multipurpose trees usually of fodder value, *Prosopis cineraria*, *Faidharbia albida*)
Protein banks	Production of protein-rich tree fodder on-farm/rangelands for cut-and-carry fodder production	Leguminous fodder trees, like *Flemingia macrophylla*, *Leucaena* spp, *Sesbania grandiflora*, *Sesbania sesban*
Plantation crops with pasture and animals	Livestock under woody perennials	Plantation crops, for example, cattle under coconuts

(Nair et al. 2021). In the Asia and Pacific region, livestock-based systems are most prevalent in all regions from arid regions of Thar desert (spread in Indian subcontinent) to humid climate of coastal India and the Pacific countries (Dagar and Gupta 2020). Agrosilvopastoral agroforestry practices in southeast Asia include trees on rangelands, protein banks and plantation crops with pastures and animals (Table 7.3).

7.3.1 *The Silvopastoral Systems for Degraded Lands*

Pastures covering about 3.4 billion ha are to a large extent under source-limited conditions and/or lack of appropriate management (Gurian-Sherman 2011). In agreement, savannas (accounting for about 30% of NPP) (Grace et al. 2006) are among the most threatened-affected biomes worldwide by land degradation and the effects of climate change meaning desertification (e.g. degradation of dry lands), because of bad grazing practices, related to high stocking animals and/or cattle farming depending on low productive native grasses (Arevalo et al. 1998).

Therefore, there is a broad potential for the implementation of silvopastoral systems in such areas and those devoted to subsistence–smallholder agriculture and/or livestock.

In addition to the general benefits of silvopastoral systems in common with other agroforestry systems (e.g. C fixation, CO_2→SOC and climate change resilience), silvopastoral systems have a comparative potential advantage associated with the grazing cycle (Nair 2012). Adequate grazing practices contribute to the increase of SOM and potential CO_2→SOC by stimulating biological activity and consequently a net nutrient mineralization–nutrient availability (See Fig 7.1 and its description). For instance, faster annual turnover of shoot materials and variations in species composition has been observed (Reeder and Schuman 2002), meanwhile reducing the production of annual forbs, also encompassing the develop of grasses with more dense and fibrous root systems (Rees et al. 2005). According to Dagar and Gupta (2020), grazing lands/range lands are not a defined landscape, these are found under different soil and climatic situations in South Asia and often exposed to overgrazing by livestock. There are immense possibilities of implementing silvopastoral systems on these degraded lands.

7.3.1.1 Silvopastoral Systems for Dry Lands

The Thar desert of India is covered by drifting or semi-stabilized sand dunes, sometimes up to 100 m in height; however, their intensity varies from place to place. These areas are also exposed to overgrazing as livestock rearing is the main livelihood resource for the people of this region. The role played by *Prosopis cineraria* in dry ecologies of India is like that of *Faidharbia albida* in Africa (Dagar et al. 2020). It is now well-established fact that it sustains rather increases the yield of both crops and forages, ameliorates the soil and gives shelter to livestock during extreme summer.

The tree is lopped frequently for its nutritive foliage and the raw pods are consumed as vegetable and ripe are part of feed for livestock. *Prosopis cineraria* is a very common tree component of agroforestry systems in arid and semi-arid areas of Indian sub-continent. The tree density varies from 5 to 250 trees per ha (Kumawat et al. 2014) depending upon rainfall; however, the tree density rarely exceeds about 50 trees per ha in the Thar desert of India (Tewari and Singh 2006).

The most important measures for sand dune stabilization are covering the area under trees and providing a surface cover of grasses followed by their protection against biotic interference. Besides fixing the sand dunes, it is important to check the movement of loose sand by applying wind breaks and mulch. Locally available woody species such as *Leptadenia pyrotechnica*, *Calligonum polygonoides* (now rare due to over-exploitation), *Ziziphus nummularia* and *Aerva tomentosa* and grasses like *Cenchrus ciliaris*, *C. setigerus*, *Lasiurus sindicus*, *Panicum turgidum* and *Saccharum munja* can be used successfully (Dagar 2012). Trees such as *Acacia tortilis*, *A. jacquimontii*, *A. leucophloea*, *A. senegal*, *Azadirachta indica*, *Balanites roxburghii*, *Prosopis cineraria*, *P. juliflora* and *Holoptelia integrifolia* in combination with grasses *Cenchrus ciliaris*, *C. setigerus*, *Dichanthium annulatum* and *Panicum antidotale* have been found most successful for sand dune stabilization.

In the dry lands of Sahel in West Africa and Eastern Africa (Kenya and Somalia, Uganda), silvopastoralism exists largely in the form of trees such as *Acacia* spp. and *Faidherbia albida* scattered on grazing lands (Bayala et al. 2014). In Eastern Africa, biomass transfer from fodder trees to livestock is a common practice using species such as *Calliandra* and *Leucaena* (Nair 2014*).* Some parklands are mono-specific (e.g. *Fadherbia albida* and *Borassus aethiopum*-based), but others have dominant tree species mixed with a range of tree and shrub species (Bayala et al. 2014). Parklands constitute the predominant forage systems in semi-arid West Africa. In the parklands, herded or penned livestock are maintained on fallow fields and surrounding grassland during the cropping season or herded, sometimes long distances, to arid but seasonal productive pastures to the north (Dagar et al. 2020). These play an important role as trees and shrubs provide soil cover that reduces erosion and buffers the impacts of climate change besides livelihood security to local people.

Live fences generally consist of a single row of densely planted trees or shrubs that are established to protect croplands from animals. Advantages of live fences as perceived by farmers in Sahel include erosion control, durability, wind break function and fodder supply (Ayuk 1997). In Burkina Faso and Mali, farmers prefer buffer strips that are comprised of *Andropogon guayanus* (efficient against wind erosion), *Euphorbia balsamifera* (medicinal properties), *Jatropha curcas* (seeds used in traditional medicine and cattle feeding), *Piliostigma reticulatum* (the leaves have medicinal properties) and *Ziziphus mauritiana* (fruits) (Spaan et al. 2004).

7.3.1.2 Silvopastoral Systems on Salt-Affected Grazing Lands

About 1 billion hectares of land are considered salt-affected and majority of these lands though unproductive are exposed to over-grazing. For sodic soils (pH > 8.5, ECe < 4 dS m^{-1}, ESP > 15), Dagar et al. (2001), Singh and Dagar (2005) and Dagar (2014) have identified and reported several suitable tree and grass species for developing successful silvopastoral systems for salt-affected soils. *Prosopis juliflora*, *P. alba*, *Acacia nilotica*, *Tamarix articulata* and *Eucalyptus tereticornis* are most successful trees for high pH (~10) soil and *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana* and *Panicum laevifolium* are suitable grass species for these soils. *Vetiveria zizanioides*, *B. mutica* and *L. fusca* also tolerate waterlogging. *Prosopis–Leptochloa* silvopastoral system has been found to be most suitable to reclaim these soils. The silvopastoral agroforestry systems, characterized by tree species of *Acacia nilotica* and *Salvodora persica* along with native grasses of *Cenchrus ciliaris* and *Panicum miliare* showed total carbon stock (Mg ha^{-1}) as: 102.81–138.23; *Acacia nilotica* + *Cenchrus ciliaris* system; 112.53–181.51 *Salvadora persica* + mixed-grass system (Kumari et al. 2018).

7.3.1.3 Silvopastoral Systems for Eroded Watersheds

Soil erosion has socio-economic, environmental and technical dimensions. Those who suffer the most are poor farmers and landless labourers, who are least able to adopt conventional measures for its control. A more beneficial alternative in eroded ecologies both high rainfall and semi-arid regions, from an ecosystem perspective, is to create a multi-functional land-use system. For example, native trees can be planted together with shade-tolerant agricultural cash crops such as coffee, cocoa, cardamom, zinger or turmeric or medicinal plants. Plantation crops like coconut may be blended suitably with spices such as clove, cardamom, black pepper and even fruits like pineapple. The sloping lands may be planted with alley crops, mainly fodder and nitrogen fixing species such as *Gliricidia sepium*, *Leucaena leucocephala*, *Cassia siamea*, *Morus alba*, *Pithecellobium dulce* and *Cajanus cajan*; and fodder grasses as inter-crops.

Woody species, mostly of fodder value found growing in eroded habitats may find priority in afforestation programme (Dagar and Singh 2018). For example, *Acacia nilotica*, *A. eburnea*, *A. leucophloea*, *A. catechu*, *Azadirachta indica*, *Albizia lebbeck*, *Balanites roxburghii*, *Butea monosperma*, *Dalbergia sissoo*, *Dendrocalamus strictus*, *Dichrostachys cinerea*, *Eucalyptus* spp., *Feronia limonia*, *Pongamia pinnata*, *Prosopis juliflora* and *Ziziphus mauritiana* have been found to adapt easily in the ravines of river Yamuna at Agra and Kshipra at Ujjain. Among grasses *Dichanthium annulatum*, *Cenchrus ciliaris*, *Bothriochloa pertusa*, *Chrysopogon fulvus*, *Themeda triandra*, *Heteropogon contortus*, *Sehima nervosum*, *Tragus biflorus*, *Iseilema laxum*, *Cynodon dactylon* and *Saccharum munja* flourish well in ravine lands.

7.3.1.4 Agropastoral Systems of Humid Regions

In some regions of the tropical Asia, silvopastoral systems involving trees (e.g. coconuts, oil palm and rubber) and animals, as well as agropastoral systems integrating crops, animals and trees (Devendra 2014). For example, in Indonesia, Malaysia Papua New Guinea, and Thailand, large, small ruminants (buffaloes and cattle) and small ruminants (goat and sheep) can be integrated in oil-palm plantations. In the humid regions, animals graze under plantations, mainly coconut. Several multipurpose trees such as *Aegle marmelos*, *Artocarpus* spp., *Bauhinia variegata*, *Erythrina variegata*, *Grewia glabra*, *Hibiscus tiliaceous*, *Moringa oleifera*, *Pitchecelobium dulce*, *Samanaea saman*, *Sesbania grandiflora*, *Morinda citrifolia* and *Trema tomentosa* can be grown in fodder banks (Dagar et al. 2014).

7.3.2 Ecological Importance of Trees in Agroecosystems

The presence of trees not only contributes to a greater C fixation being also increases the potential utilitarian and consumer assets, but in agroforestry systems, the trees also operate as active or passive banks of protein (e.g. browsing in silvopastoral systems) without compromising yields and animal wellness when properly managed (Clough et al. 2011). Furthermore, agroforestry systems has been recognized as recommended land use, able to play complementary roles other than food production, such as buffer spaces for conservation of biodiversity, depending on the combination tree species-density-arrangement (Vandermeulen et al. 2018; Harvey et al. 2008; Tscharntke et al. 2011). This is because trees serve as seed producers and providers of habitat and food for animals (Kabir and Webb 2007) and can be used in buffer zones or biological corridors (Donald 2004; Mas and Dietsch 2004) (See Fig. 7.1 and its description), compared to agricultural areas (being commonly fragmented and degraded systems low in biodiversity).

Desirable characteristics of trees when establishing silvopastures, most often include production of trees and tree products such as barks, fruits and nuts, and leaves. Tree species like *Parkia biglobosa*, *Balanites aegyptiaca*, *Adansonia digitata*, *Bauhinia rufescens*, *Faidherbia albida* and *Sclerocarya birrea* are commonly found in silvopastoral systems in Africa. Several leguminous shrub and tree species are used as sources of fodder for cattle and small ruminants in semiarid and subhumid tropical zones. The most frequently browsed species in the tropics are listed in Table 7.4.

7.3.3 Considerations Prior to Silvopastoral Systems Establishment

Competitive interactions in the silvopastoral systems understory for light, moisture and nutrients have been observed, which may lead to diverse adverse effects (e.g. nutrient uptake levels, yield loss, reduction of plant growth and increased mortality) (Mead 2009), and losses of SOC via increased tree-understory development (Upson et al. 2016). Moreover, animal–plant interactions could also result in detrimental outcomes, including premature fruit drop by trees (e.g. some pines, *Cupressus* sp.) (Fisher 2007), higher parasite loads on livestock under shade (e.g. pines) (Mead 2009) and damage to young trees via browsing (Mead et al. 1999). Therefore, the species selection, tree density-distribution/shadow rate, type of management practices and cattle loads are some of key criteria that should be considered prior to silvopastoral systems establishment and during the initial operative activities.

In developing regions (e.g. semiarid) silvopastoral systems consist of open grazing by free-roaming animals under scattered natural areas of trees and shrubs (Nair 2012), and regions where there is frequent utilization of halophytes (e.g. plants

Table 7.4 Some important fodder trees and shrub species in the tropics (adapted from Atangana et al. 2014 based on Nair et al. 1984; Lefroy et al. 1992; Devendra and Sevilla 2002)

Species	Family	Origin
Faidherbia albida	Fabaceae	Africa
Acacia ataxancatha	Fabaceae	Africa
Acacia mellifera	Fabaceae	Africa
Acacia tortilis	Fabaceae	Africa
Afzelia africana	Fabaceae	Southeast Asia
Albizia chinensis	Fabaceae	India, Southeast Asia
Albizia lebbeck	Fabaceae	India, Southeast Asia
Balanites pedicellaris *B. aegyptiaca*	Balanitaceae (Zygophyllaceae)	Africa
Bridelia micrantha	Phyllanthaceae	Africa
Cajanus cajan	Fabaceae	Africa, Asia
Crotalaria goodiformis	Fabaceae	Africa
Erythrina variegata	Fabaceae	Africa, Southeast Asia
Flemingia macrophylla	Fabaceae	Southeast Asia
Leucaena spp	Fabaceae	Africa, Southeast Asia
Sesbania grandiflora	Fabaceae	Southeast Asia
Sesbania sesban	Fabaceae	Africa, Southeast Asia
Tamarindus indica	Fabaceae	Africa
Ficus thonningii	Moraceae	Africa
Gliricidia sepium	Fabaceae	Mexico to Peru

in edaphic environments with at least 200 mM of salt concentration) for feed purposes, which represents a challenge, mostly due to the high salt content of the plants and the consequent nutritional constraints for animal feed (Öztürk et al. 2019). However, to accurately assess the nutritional value of a particular species for its potential use as fodder in silvopastoral systems and how it regulates animal preferences-behaviour-productivity, is necessary to determine the different properties which influence its palatability such as dry matter, ashes content, crude protein, neutral detergent fibre, metabolizable energy, amino acids and fatty acids (Schmidt and Alonso 2016).

Another important aspect to consider before silvopastoral systems implementation (and agroforestry systems in general) is the legal frame concerning '*regulatory managements*' in order to avoid conflicts of interest (e.g. land tenure) between farmers—local communities—and large states supported by governments. Van Noordwijk et al. (2008) stated the principal issues restricting the potential for farmers planting trees and establishing agroforestry systems in general include: (1) inconsistent terminology for forest, plantations and reforestation, (2) limited accessibility to appropriate planting material, (3) lack of management skills and information linking products to lucrative markets, (4) overregulation of logging mostly restricting the marketing of tree sub-products, (5) lack of rewards for enhanced environmental services after agroforestry systems–silvopastoral systems adoption, (6) lack of legal and institutional frameworks supporting agroforestry systems–silvopastoral systems.

7.4 Carbon Sequestration in Silvopastoral Systems

The factors controlling the functional aspects of agroforestry systems (CO_2→SOC, or climate change mitigation) are: (1) plant attributes: tree species, age, density, specific crops, biodiversity; (2) amount and quality of biomass inputs; (3) climatic conditions: altitude, wind, precipitation; and iv) soil properties: SOC content, structure, texture, fertility status (Nair 2012; Gold and Garrett 2009; Feliciano et al. 2018; Cardinael et al. 2018). According to Lorenz and Lal (2014) and Nair (2012), in agrosystems with a marked presence of woody species (e.g. agroforestry systems), high amounts of SOM are produced that results in net annual increases of ecosystem C, of which about 60% of C is in the form of SOC. The mean C stocks in agroforestry systems have been estimated at 300 Mg SOC ha^{-1} (0–1 m depth), with a potential capacity to mitigate up to 2% of the annual global C emissions (Lorenz and Lal 2014).

However, the C fixation or aboveground C capture in agroforestry systems occurs in the aerial structures (e.g. stem, canopy) (50–60%), in the grass (10%) and the remainder in form of belowground structural C (root systems) (Sharrow and Ismail 2004). Moreover, it has been observed that individual trees in agroforestry systems develop faster than those in forests, allowing greater comparative C fixation rates (Sharrow and Ismail 2004). Africa shows the greatest agroforestry systems diversity, being alley cropping and improved fallows the most common systems (based on 25 and 17 publications, respectively), which also achieve the highest C fixation rates (12.95 Mg C ha $year^{-1}$)

However, Feliciano et al. (2018) pointed out the importance of considering the temporal C variations in agroforestry systems, since there are net losses immediately after the implementation of an agroforestry systems, then gradually there is increasing C fixation as a result of system-age/tree growing cycle: establishment phase (0–5 year) > initial phase (5–10 year) > full vigour phases (>10 year), finally a decline (>15 year) is experienced, tending to the steady state (e.g. null C fixation) at maturity, depending on species characteristics, site nutrient status, climatic conditions and management

Others, however, have reported that upon the adoption of agroforestry systems there is a positive but variable result in terms of CO_2→SOC, where many drivers may influence the outcome, including: amount of biomass inputs, previous land use, soil disturbances during agroforestry systems establishment, pedo-climatic conditions, type and specific properties of the adopted agroforestry systems (e.g. tree species-density), and management characteristics (Cardinael et al. 2018). Both the aboveground C fixation and CO_2→SOC rates as estimated by agroforestry systems type are provided in Table 7.5. The variations of CO_2→SOC capacity (Mg C ha $year^{-1}$) depend on previous land uses, whereby Cardinael et al. (2018) estimated:

Table 7.5 Global C capture capacity reported for distinct agroforestry systems

System	C fixation (Mg C ha^{-1} $year^{-1}$)	$CO_2 \rightarrow SOC$ (Mg C ha^{-1} $year^{-1}$)
Alley cropping	1.65	1.87
Homegardens[a]	2.18	0.95
Improved fallows[b]	7.13	1.91
Shadow systems[c]	2.57	1.48
Silvopastoral systems	1.28	3.30
Woodlots	6.35	0.34

Source: Feliciano et al. (2018)

[a] Refers to diverse animal-herbaceous-tree species on small parcels surrounding homestands

[b] Planning trees (mostly legume species) emplaced over degraded soils in order to enrich soil in relative short periods

[c] Combination of tea/cocoa/coffee shrubs with multipurpose shade species

cropland to agroforestry systems (+0.75 ± 0.19), forest to agroforestry systems (1.15 ± 1.02). Feliciano et al. (2018) estimated changes of $CO_2 \rightarrow SOC$ from previous land managements into agroforestry system types as follows: rangelands to homegardens (+3.8 ± 1.54), croplands to improved fallows (+1.9 ± 1.9) and grasslands to silvopastoral systems (+4.4 ± 0.86).

In silvopastoral systems, direct carbon inputs to the soil occurs in the form of the litterfall from the trees, organic matter inputs from grazing livestock, and input of belowground residue by woody species in both topsoil and subsoil. Specifically, studies on silvopastoral systems have reported that 1–5 Mg C ha $year^{-1}$ are captured in aboveground biomass (Ibrahim et al. 2010), and belowground, SOC accumulation rates of 1.8–7.5 Mg ha^{-1} $year^{-1}$ have been observed (Alonso 2011; Udawatta and Jose 2011; Feliciano et al. 2018; Ortiz et al. 2020). The conversion of grasslands to silvopastoral systems leads to the highest total estimated C accumulation (4.4 Mg C ha $year^{-1}$) (Feliciano et al. 2018).

These aforementioned rates depend on: (1) the previous land use, and which woody species are to be incorporated into currently managed pastures, or vice versa, to create the silvopastoral systems (Gordon et al. 2005), the amount of diversification to be introduced to intensive monoculture plantation systems (Peri et al. 2017), or whether there is reclamation of degraded forest (Ortiz et al. 2020) and prairies before silvopastoral systems (Dube et al. 2011), or cropland to be converted to silvopastoral systems (Cardinael et al. 2018) (2) the dominant pedo-climatic-ecological conditions, (3) species selection and their density-spatial arrangement within silvopastoral systems, and (4) silvopastoral systems operative efficiency (main objective purpose, debris management, etc.) (Cardinael et al. 2018).

Silvopastoral systems have been reported to produce the highest $CO_2 \rightarrow SOC$ conversion rates among the different agroforestry systems (Feliciano et al. 2018), which have been documented in regions such as Europe (Rigueiro-Rodríguez et al. 2008) and North America (Udawatta and Jose 2011).

7.4.1 Regional Carbon Sequestration in Asia and Africa Through Silvopastoral Systems, Identity Traits and Reported Benefits

A remarkable variability in composition, structure, purposes and practices besides livestock (e.g. pruning, pollarding) has been documented in traditional silvopastoral systems in Asia and Africa (Jose et al. 2017). For instance: (1) *Hanunoo* farming systems in Philippines (e.g. trees providing new foliage and shadow to prevent excessive exposure to solar radiation/to maintain appropriate moisture levels at the end of rice-growing season, while either planted or native trees provide food, medicines, wood) (Conklin 1957), (2), *Taungya* systems, consisting on crop production for a relative short period (4–5 years) within young forest plantations for commercial purposes when mature (e.g. Nigeria, Kenya) (Imo 2009), (3) *Galajars*, referring traditionally exploited stands adjacent to pristine forests, covering about 5.3 million ha in Iran (Valipour et al. 2014), (4) in vast regions such as Nigeria, typically some crops such as maize, pumpkins, yams, beans among other, are grown together under a cover of scattered trees at smallholder-homestead level (Forde 1937), to as subsidiary agriculture involving in some regions (e.g. Zambia) (Anon 1938), (5) in both Continents, the reclamation-productivity of salt affected areas through silvopastoral systems including salt-adapted trees, fodder species and halophytes (Gupta et al. 2020), (6) *Ngitili*: traditional Tanzanian strategies for grazing and food security, in which the vegetational components (e.g. trees, shrubs grasses) during the wet season to later enable grazing within the dry season in order to avoid erosion and other land degradation processes (Kamwenda 2002). The last illustrates a significant presence of traditional—local knowledge within silvopastoral systems, which also may reflect the transversal prevalence of smallholder category and a strong cultural rootedness (e.g. primarily scattered native trees) (Jose and Dollinger 2019; Sales-Baptista and Ferraz-de-Oliveira 2021). There are some examples reported in literature regarding silvopastoral systems benefits in Asia and Africa for carbon sequestration (Table 7.6).

7.4.2 Biophysical Mechanisms for C Sequestration in Silvopastoral Systems

The continuum biomass production in silvopastoral systems (e.g. foliage-litterfall, faeces), which is generated from the interaction of silvopastoral systems components, results not only in C fixation but in the formation of fresh SOM (or SOC) (Nair 2012; El-Ramady et al. 2014), which is a crucial component that also controls most of the aforementioned soil and terrestrial ecosystem processes (Baldock and Nelson 2000; Lal 2015; Heaton et al. 2016) and is a key component of land degradation assessment and potential of climate change mitigation. A summary of the synergistic

Table 7.6 Some reported data in silvopastoral systems C_{SEQ} in Asia and Africa

Location	Main features	SOC stock/ C_{SEQ} (Mg C ha^{-1}/Mg C ha^{-1} $year^{-1}$)	Aboveground C stock/C fixation in biomass (Mg C ha^{-1}/Mg C ha^{-1} $year^{-1}$)	Reference
Gujarat, India	A total of 4 plots (11-year-old), comprised of associations of: (a) *Acacia tortilis*—*Cenchrus ciliaris*, (b) *Acacia tortilis*—*Cenchrus setegerus*, (c) *Azadirachta indica*—*Cenchrus ciliaris*, (d) *Azadirachta indica*—*Cenchrus setegerus* of 278 steams ha^{-1} each, measured at 0–40 cm depth	(a) 19.22/ 0.52 (b) 18.39/ 0.69 (c) 17.66/ 0.37 (d) 14.43/ 0.33	(a) 12.93/0.45 (b) 12.55/0.33 (c) 17.66/0.46 (d) 14.43/0.32	Mangalassery et al. (2014), Cardinael et al. (2018)
Rajasthan, India	A 30-year-old system with a tree density of 333 stems ha^{-1}, comprised by *Hardwickia binata*—*Cenchrus setigerus*	22.5 ± 9.5/ NR	82.4 ± 34.8	Gupta et al. (2017)
Rajasthan, India	A 30-year-old system with a tree density of 666 stems ha^{-1}, comprised by *Hardwickia binata*—*Cenchrus setigerus*	31.6 ± 12.6/ NR	116.1 ± 46.2	Gupta et al. (2017)
Kjammam, India	A 4-year-old system having 4444 stems ha^{-1}, of *Eucalyptus*—*Vigna unguiculata* associations	NR/NR	34	Prasad et al. (2012)
Kjammam, India	A 4-year-old system having 10,000 stems ha^{-1}, of *Eucalyptus*—*Vigna unguiculata* associations	NR/NR	62	Prasad et al. (2012)
Tanzania	A 20-year-old system comprised of an (a) reserved and (b) degraded *Vachellia drepanolobium* based systems at 0–20 cm depth	(a) 19.86/ NR (b) 7.77/ NR	NR	Osei et al. (2017)

NR not reported

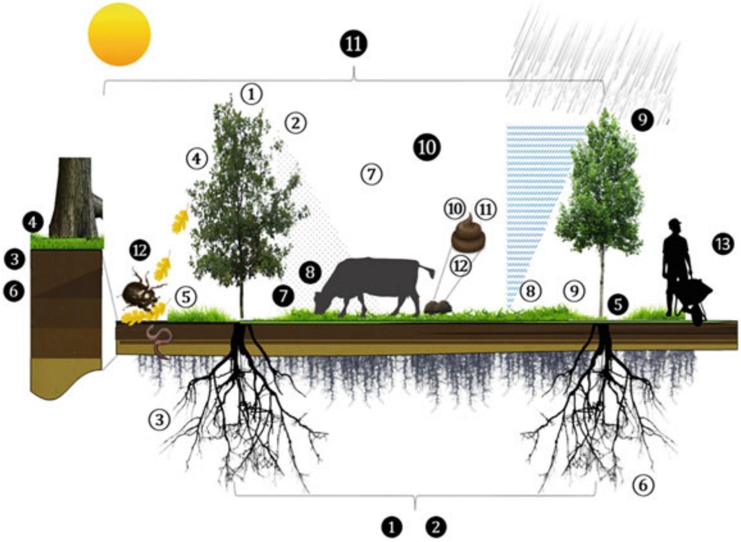

Fig. 7.2 Main biophysical mechanisms involving C→SOC, CO_2eq emission reduction and soil quality improvement in silvopastoral systems: (i) as individual functions: ① Stress reduction, ② Bio-protection, ③ Internal resource cycling, ④ C fixation ⑤ Biomass input/SOM chemical protection, ⑥ Depth exploration, ⑦ Regulation of temperature-moisture fluxes, ⑧ Improvement of herbaceous resilience, ⑨ Mutualism, ⑩ Medium-term critical nutrient bio-disponibilization and SOM mineralization, ⑪ Short term critical nutrient bio-disponibilization and SOM mineralization, and ⑫ Direct input of organic matter; (ii) as component interactions: ❶ Shrinking of dissolved C (DOC) losses, ❷ Groundwater pollution protection, ❸ Direct input of organic matter-nutrients, promoting SOM cycling, ❹ Bio-disponibilization, ❺ Dietary diversification, ❻ Physical and chemical protection of SOM, ❼ Increase of digestibility, ❽ Rotational grazing, ❾ -Bio-construction, ❿ Generation of microclimatic conditions, ⓫ Autonomy, ⓬ Increase of biodiversity, resilience, dynamic of SOM, and ⓭ Human well-being

processes within silvopastoral systems is graphically described in Fig. 7.2 and subsequently analysed in Table 7.7.

However, competitive interactions in the silvopastoral systems understory for light, moisture and nutrients have been observed, that may lead to diverse adverse effects (e.g. nutrient uptake levels, yield loss, reduction of plant growth and increased mortality) (Mead 2009), and losses of SOC via increased tree-understory development (Upson et al. 2016). Moreover, animal-plant interactions could also have detrimental influences, including premature fruit drop by trees (e.g. some pines, *Cupressus* sp.) (Fisher 2007), higher parasite loads on livestock under shade (e.g. pines) (Mead 2009) and damage to young trees via browsing (Mead et al. 1999). Therefore, the species selection, tree density-distribution, type of management practices and cattle loads are some of key criteria that should be considered prior to silvopastoral systems establishment and/or during the initial stage of operational activities.

Table 7.7 Main bio-physical mechanisms involving C→SOC, CO_2eq emission reduction and soil quality improvement in silvopastoral systems: details of Fig. 7.2

ID	Functions—interactions	Reference
① W	Core element for specific purposes of the silvopastoral system: (1) ecological sustaining-improving through the inclusion of native, N-fixing (e.g. *Hippophae rhamnoides*, *Alnus incana*) and/or fast-growing species (e.g. *Populus* sp.), (2) species of social-economic interest (e.g. timber production, fruit trees)	Nair et al. (1999), Gordon et al. (2005), Jose et al. (2017)
② W	Promoting animal welfare trough shading, providing temperatures around the animal-thermoneutral zone and protecting new-born individuals (e.g. chilling) and offspring survival	Hu et al. (2005), Murgueitio et al. (2013), Broom et al. (2013)
③ W	Limiting moisture losses via canopy (e.g. evaporation recapture, reducing potential hydric stress) and nutrient leaching (e.g. assimilation of residual NO_3^-), also reducing the impact of erosive agents (e.g. raindrop impact)	Buresh and Tian (1997), Murgueitio et al. (2013), Ong and Kho (2015), Kunst et al. (2016), Jose et al. (2017)
④ W	By reducing aboveground-belowground-C:N ratios, including about 22% more C stored in woody elements compared to intensive land uses (e.g. plantations)	Dube et al. (2011)
⑤ W	Litterfall-debris rich in lignin, reduce SOC mineralization in respect to agricultural systems. However, litterfall also provides up to 90% of nutrients required for herbaceous component	Buresh and Tian (1997)
⑥ W	Root exploration increases soil moisture retention and porosity, penetration resistance compared to cropland/grassland. water holding capacity and infiltration capacity improvement, regulation of hydrological cycle	Buresh and Tian (1997), El-Ramady et al. (2014)
⑦ H	Promoting the protection-development of topsoil by a permanent cover, avoiding the emission of water vapour, also preventing preferential flow pathways (e.g. formation of rills-gullies). Less sensitive to shade than other agroforestry systems	Giller et al. (1997), Montagnini and Nair (2004), Cardinael et al. (2017)
⑧ H	The use of mixed species may enhance resistance to environmental changes, potential diseases and pests	
⑨ H	Combination of forage and N-fixing species, facilitating availability of a critical nutrient and incorporating SOC even more efficiently than trees Increases yield of 100% have been	De Stefano and Jacobson (2017), Saarijärvi and Rukajarvi (2009)

(continued)

Table 7.7 (continued)

ID	Functions—interactions	Reference
	observed compared to monoculture-pastures	
⑩ A	Faeces increase soil nutritional status with contributions of P, K, Mg, Ca and N. This last is about 90% in organic forms, which is slowly released (24-month period) in forms of NO_3^-, preferred by woody plants. Cattle contribution on soil fertility includes about: 6.9, 7.5 and 4.5 mg kg^{-1} of N, P and K respectively	Saarijärvi and Rukajarvi (2009), Rochette et al. (2014), Uscola et al. (2014), Bélanger et al. (2015)
⑪ A	Urine contributes with readily useful (weeks period) N (NH_4^+), which is utilized primarily by herbaceous component, commonly resulting in higher growth rates, yield and coverage	Saarijärvi and Rukajarvi (2009), Uscola et al. (2014)
⑫ A	Livestock introduces litter into mineral soil via trampling, increasing around 12% SOC within 0–15 cm. Livestock is also effective in the weed control-herbaceous competition and preventing potential wildfires by keeping the vegetation sparse	Naeth et al. (1991), Hewins et al. (2018)
❶ W↔W	Reduction in nutrient - C losses via leaching (e.g. dissolved organic C (DOC)) (depth >0.6 m), probably via mutualism root-mycorrhizae	Dupraz and Liagre (2008), Dube et al. (2011)
❷ W↔W	Root associations limit lixiviation processes of potentially harmful compounds (e.g. NO_3^-)	Beaudoin et al. (2005), Dupraz and Liagre (2008)
❸ W↔H	Root exudates endorse biological activity, where tree roots introduce organic matter in deep soil, out of the rhizosphere and herbaceous roots acts as a green manure, contributing around 50–92.7% of stable SOC	Odhiambo et al. (2001), Sokol et al. (2019)
❹ W↔H	Functioning as a bank of protein and nutrients and animal health protection, including productivity (growth rates), and the reduction in parasite infestation Common inclusion of N- fixing species (about 650 available woody species, able to fix 100–500 kg N ha $year^{-1}$), transferring N to animals via fibre (about 120 kg N ha^{-1} required) and other vegetal components via soil solution N fixing diet (via condensed tannins) also provides increases in reproductive rates, expansion of immune cells, reduction in nematode parasite fecundity, parasite	Nguyen et al. (2005), Nair et al. (1999), Odhiambo et al. (2001), Mupeyo et al. (2011), Pitta et al. (2005), Ramírez-Restrepo et al. (2010), Sarvade et al. (2019)

(continued)

Table 7.7 (continued)

ID	Functions—interactions	Reference
	populations and favouring helminthic control	
❺ H↔A	Leaf complementary diet (e.g. *Carpinus betulus*, *Corylus avellana*) t rather than solo grain ensures both, usability of non-profitable resources for humans and the reduction of ecological pressure linked to intensive fodder production (e.g. soybean)	Broom et al. (2013), Beaudoin et al. (2005), Vandermeulen et al. (2018)
❻ W↔H	Root systems from both woody and herbaceous (exudates and other forms of SOM), promotes the formation of stable aggregates. organo-mineral associations (avoiding potential toxic elements such as Al^{+3}), and the formation of condensed organic matter (e.g. humic substances)	Giller et al. (1997), Buresh and Tian (1997), Kunst et al. (2016)
❼ H↔A	Introduction of rumen fermentation modifiers species, having high contents of saponins-tannins with associated anti-protozoa-methanogenic properties up to 22% more than intensive livestock farming	Galindo (2004), Hu et al. (2005), Sarvade et al. (2019)
❽ A↔H	Animal habits have a key roil on (1) promoting plant propagation, (2) reducing the risk of fire generation—propagation, and (3) generating a green cover, reducing in about 16–40% the weeding costs	Lacorte et al. (2016), Sarvade et al. (2019)
❾ WHA ≡	The optimization in the use of local resources (about 40% more) compared to intensive land uses (e.g. plantations), results in a more efficient growth of tree aerial-lateral structures (e.g. aboveground C), ultimately SOC input	Dube et al. (2011)
❿ WHA ≡	Modification of different environmental parameters (e.g. air and soil temperature (0–5 cm), % relative humidity, total radiation, wind speed, evapotranspiration	Dube et al. (2011), Jose et al. (2017)
⓫ WHA ≡	Limiting requirements of external inputs (e.g. energy) compared to mono-biotic and conventional systems (e.g. fuels, manure management)	Nair et al. (1999), Moreno et al. (2014)
⓬ WHA ≡	Promoting connectivity between landscape fragments. Associated environmental services including pollination, pest and weed control, translocation of SOM (e.g. bioturbation)	Odhiambo et al. (2001), Ibrahim et al. (2010)
⓭ WHA ≡	Improving job satisfaction, promoting food security, family–social integration, economic production, poverty reduction,	Ispikoudis and Sioliou (2005), Broom et al. (2013), Montagnini et al. (2013)

(continued)

Table 7.7 (continued)

ID	Functions—interactions	Reference
	considering a global decline of household food production in rural sectors of approximately 60%	

Different components: *W* Woody, *H* herbaceous, *A* animal; ⓪ functions; ❶: interactions [↔ two component interaction, ≡ three component interaction]

7.4.2.1 Individual Mechanisms

In the next section, the principal mechanisms related to C capture and storage, nutrient re-cycling/retention and SQ improvement in silvopastoral systems are presented:

7.4.2.2 Influence of SPP on Changing Soil Quality

Silvopastoral systems can store and conserve C in vegetation and soil, increase SOC stock (e.g. $CO_2 \rightarrow$SOC) progressively influence physical, chemical and biological soil properties and ensuring the associated ecological benefits (Sollins et al. 1996). In different studies it has been demonstrated the positive variations of soil properties and ecosystems services (e.g. SI_{ND}) apart from $CO_2 \rightarrow$SOC due to silvopastoral systems management, such as: (1) improving water cycling and retention: by reduction of soil bulk density, increased water infiltration capacity, and reduced mechanical resistance, (2) improving nutrient status (by increased total and available N, and K), (3) improving sorption–desorption by decreased soil acidity, and greater immobilization of pollutants and potential toxic ions by reducing aluminium saturation (Arevalo et al. 1998; Blanco-Canqui and Lal 2008; Ortiz et al. 2020).

7.4.2.3 Contributions of Silvopastoral Systems for Offsetting Greenhouse Gases (GHG) Other Than CO_2

With reference to the potential of silvopastoral systems to counteract emissions from different sources than CO_2, diverse evidence has been reported:

Methane (CH_4^+) Agriculture causes 50% of the global CH_4^+ emissions, out of which 32.7–39% (80 Tg) are from enteric fermentation (e.g. biological process of macromolecular break down in the rumen of livestock) (Moumen et al. 2016). Extensive grazing (rangelands), tends to deplete valuable resources of fodder, leading to the intake of lower quality forages (having less than 45% digestibility) (e.g. perennials/poorly palatable species with low concentrations of crude protein, and having high levels of complex molecules such as lignin). Additionally, intensive livestock management requires massive production of fodder at a high environmental cost (Steinfeld 2006; Sarvade et al. 2019). However, in silvopastoral systems, it is common to include N-fixing species that contain condensed tannins and saponins with medium to high values of digestibility (55–85%) that decrease CH_4^+ emissions by 12–15% (Steinfeld 2006; Montagnini et al. 2013).

Moreover, soils can act as CH_4^+ sinks via two main mechanisms: (1) direct diffusion of CH_4^+ into pore spaces and (2) methanogenic bacteria oxidation to CO_2. Edaphic factors controlling CH_4^+ intake include BD, soil moisture and pore architecture-effective porosity (Priano et al. 2017). Since tree-based land managements (e.g. AF silvopastoral systems) promote: (1) favourable soil structural processes, (2) soil biodiversity and a more efficient water cycling (moisture trapping via the tree canopy), they also actively contribute to CH_4^+ sequestration (Priano et al. 2020).

The same authors found 100% and 204% higher CH_4^+ intake (ng CH_4^+ m^{-1} s^{-1}) in a pine plantation in the Province of Buenos Aires, Argentina, compared to conterminous rangelands and croplands, respectively.

Nitrous Oxide (N_2O) Livestock production is a source of 75–80% of N_2O emissions from agricultural activities, (65% of overall global emissions) (Steinfeld 2006), since N is inefficiently used by animals (only 5–30% of the N in feed) (Oenema et al. 2008). Specifically in the case of N_2O emissions, livestock generates at least 1.8 Tg N $year^{-1}$, which represents 33% of the global agricultural emissions (Syakila and Kroeze 2011; Skiba and Rees 2014).

Other major sources of N_2O are a consequence of: (1) the application of synthetic N fertilizers (~120 Tg N $year^{-1}$), which is an equivalent amount to that captured by global processes of biological N fixation (Smith 2017) and (2) anthropogenic soil disruptions (e.g. tillage, fertilization processes), where low aeration (oxygen levels) in combination with other factors (e.g. presence of SOC_{LF} and slightly acid to alkaline pH), that lead to denitrification events in soils. Intensive agriculture also generates diffuse emissions based on N losses from soil (e.g. leaching of NO_3^-, and in contained in runoff), where N_2O is subsequently formed outside the soil system (e.g. superficial water bodies) (Syakila and Kroeze 2011; Skiba and Rees 2014).

Nevertheless, in silvopastoral systems, the use of N-fixing species may partially or totally decrease the necessity of N fertilizers, thereby: (1) the necessity of their direct utilization, (2) limiting NO_3^- leaching-denitrification that could produce N gas, and (3) minimization of their contribution to global emission of the 14 Tg CO_2 that annually emanate from commercial fertilizer production (Steinfeld 2006).

7.5 Conclusions

Silvopastoral systems (and agroforestry systems in general) are among the main global recommended land uses, promoting social integration and also able to reverse different land degradation processes such as SOC depletion, soil erosion, soil compaction, pests, species migration-extinction through their complex biophysical interactions, resulting on a continuous SOM-SOC production, which has been recognized as one of the most reliable terrestrial variables to measure ecosystem productivity. Since land degradation originates mainly in the soil, it is necessary to periodically assess different soil properties and processes apart from SOM, or, in other words, to monitor the effects of SOM on other important parameters of soil quality (SQ). However, the use of SQ has not received enough attention in the literature as a complementary tool addressing land degradation. Despite the foregoing and other literature documenting the importance and transcendence of the implementation of recommended land uses, for instance, there has been reported that only about 7% of conversion to no tillage systems from conventional agriculture (Derpsch 2011). Finally, it is necessary to not lose sight that the primary and most valuable opportunity to confront land degradation and climate change effects is the reduction of widespread land-use change, mainly through conversion of natural ecosystems to unsustainable biomass production models (e.g. mono-biotic, conventional and/or industrial agriculture). However, land degradation control at the local level is difficult for small farmers and landholders from developing countries because of limited resources, which triggers the vicious cycle of 'land degradation-poverty'.

References

Akinnifesi FK, Makumba W, Sileshi G, Ajayi OC, Mweta D (2007) Synergistic effect of inorganic N and P fertilizers and organic inputs from *Gliricidia sepium* on productivity of intercropped maize in Southern Malawi. Plant Soil 294(1–2):203–217

Alavalapati JRR, Shrestha RK, Stainback GA, Matta JR (2004) Agroforestry development: an environmental economic perspective. Agrofor Syst 61–62(1–3):299–310

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259(4):660–684

Alonso J (2011) Silvopastoral systems and their contribution to the environment. Cuba J Agric Sci 45(2):107–114

Anon (1938) Report on the financial and economic position of Northern Rhodesia. British Government, Colonial Office, p 145

Arevalo LA, Alegre JC, Bandy DE, Szott LT (1998) The effect of cattle grazing on soil physical and chemical properties in a silvopastoral system in the Peruvian Amazon. Agrofor Syst 40(2): 109–124

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. Agric Ecosyst Environ 88(2):153–160

Aryal DR, Gómez-González RR, Hernández-Nuriasmú R, Morales-Ruiz DE (2019) Carbon stocks and tree diversity in scattered tree silvopastoral systems in Chiapas, Mexico. Agrofor Syst 93(1): 213–227

Atangana A, Khasa D, Chang S, Degrande A (2014) Tropical agroforestry. Springer, Dordrecht

Ayuk ET (1997) Adoption of agroforestry technology: the case of live edges in the Central Plateau of Burkina Faso. Agric Syst 54(2):189–206

Baldock JA, Nelson PN (2000) Soil organic matter. In: Sumner M (ed) Handbook of soil science. CRC Press, Boca Raton, pp B25–B84

Barbier EB, Hochard JP (2018) Land degradation and poverty. Nature Sustainab 1(11):623–631

Batir JF, Hornbach MJ, Blackwell DD (2017) Ten years of measurements and modeling of soil temperature changes and their effects on permafrost in Northwestern Alaska. Glob Planet Chang 148:55–71

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Beaudoin N, Saad JK, Van Laethem C, Machet JM, Maucorps J, Mary B (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. Agric Ecosyst Environ 111(1–4):292–310

Beer J, Harvey CA, Ibrahim M, Harmand JM, Somarriba Chavez E (2003) Congress proceedings. XII world forestry congress: forests, source of life. Forests for the planet. Bibliothèque Nationale du Québec, Québec, pp 417–424

Bélanger G, Rochette P, Chantigny M, Ziadi N, Angers D, Charbonneau É, Pellerin D, Liang C (2015) Nitrogen availability from dairy cow dung and urine applied to forage grasses in eastern Canada. Can J Plant Sci 95:55–65

Blanco-Canqui H, Lal R (2008) Principles of soil conservation and management. Springer, Cham, p 617

Broom DM, Galindo FA, Murgueitio E (2013) Sustainable, efficient livestock production with high biodiversity and good welfare for animals. Proc R Soc B Biol Sci 280(1771):20132025

Buresh RJ, Tian G (1997) Soil improvement by trees in sub-Saharan Africa. Agrofor Syst 38(1): 51–76

Cardinael R, Chevallier T, Cambou A, Béral C, Barthès BG, Dupraz C, Durand C, Kouakoua E, Chenu C (2017) Increased soil organic carbon stocks under agroforestry: a survey of six different sites in France. Agric Ecosyst Environ 236:243–255

Cardinael R, Umulisa V, Toudert A, Olivier A, Bockel L, Bernoux M (2018) Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environ Res Lett 13(12):124020

Clough Y, Barkmann J, Juhrbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darras K, Putra DD, Erasmi S, Pitopang R, Schmidt C, Schulze CH, Seidel D, Steffan-Dewenter I, Stenchly K, Vidal S, Weist M, Tscharntke T (2011) Combining high biodiversity with high yields in tropical agroforests. Proc Natl Acad Sci 108(20):8311–8316

Conklin HC (1957) Hanunoo agriculture. A report on an integral system of shifting cultivation in the Philippines (Forestry Development Paper 12). Food and Agricultural Organization of the United Nations, Rome

Coppus R, Imeson AC (2002) Extreme events controlling erosion and sediment transport in a semi-arid sub-andean valley. Earth Surf Process Landf 27(13):1365–1375

Dagar JC (2012) Utilization of degraded lands/habitats and poor-quality water for livelihood security and mitigating climate change. Indian J Agroforestry 14(1):1–16

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services, Advances in Agroforestry, vol 10, pp 273–332

Dagar JC, Gupta SR (2020) Silvopasture options for enhanced biological productivity of degraded pasture/grazing lands: an overview. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore, pp 163–227. https://doi.org/10.1007/978-981-15-6807-7_6

Dagar JC, Singh AK (eds) (2018) Ravine lands: greening for livelihood and environmental security. Springer, Singapore, p 636

Dagar JC, Singh G, Singh NT (2001) Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali soils in India. Arid Land Res Manag 15:115–133

Dagar JC, Singh AK, Arunachalam A (eds) (2014) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, Dordrecht, p 400
Dagar JC, Gupta SR, Teketay D (eds) (2020) Agroforestry for degraded landscapes: recent advances and challenges. Springer, Singapore, p 554
De Fries RS, Asner GP, Houghton RA (2004) Ecosystems and land use change, vol 153. American Geophysical Union, Washington
De Stefano A, Jacobson MG (2017) Soil carbon sequestration in agroforestry systems: a meta-analysis. Agrofor Syst 92:285–299
Derpsch R (2011) Frontiers in conservation tillage and advances in conservation practice
Devendra C (2014) Perspectives on the potential of silvopastoral systems. Agrotechnology 3(1):8. https://doi.org/10.4172/2168-9881.1000117
Devendra C, Sevilla CC (2002) Availability and use of feed resources in crop-animal systems in Asia. Agric Syst 71(1–2):59–73
Dixon MJR, Loh J, Davidson NC, Beltrame C, Freeman R, Walpole M (2016) Tracking global change in ecosystem area: the wetland extent trends index. Biol Conserv 193:27–35
Donald PF (2004) Biodiversity impacts of some agricultural commodity production systems. Conserv Biol 18(1):17–38
Dotterweich M (2013) The history of human-induced soil erosion: geomorphic legacies, early descriptions and research, and the development of soil conservation—a global synopsis. Geomorphology 201:1–34
Dou X, Zhou W, Zhang Q, Cheng X (2016) Greenhouse gas (CO_2, CH_4, N_2O) emissions from soils following afforestation in central China. Atmos Environ 126:98–106
Dube F, Thevathasan NV, Zagal E, Gordon AM, Stolpe NB, Espinosa M (2011) Carbon sequestration potential of silvopastoral and other land use systems in the Chilean Patagonia. In: Kumar BM, Nair PK (eds) Carbon sequestration potential of agroforestry systems, vol 8. Springer, Cham, pp 101–127
Dupraz C, Liagre F (2008) Agroforesterie: des arbres et des cultures, 1st edn. France Agricole, Paris, p 413
Ellis EC, Kaplan JO, Fuller DQ, Vavrus S, Klein Goldewijk K, Verburg PH (2013) Used planet: a global history. Proc Natl Acad Sci 110(20):7978–7985
El-Ramady HR, Alshaal TA, Amer M, Domokos-Szabolcsy É, Elhawat N, Prokisch J, Fári M (2014) Soil quality and plant nutrition. In: Ozier-Lafontaine H, Lesueur-Jannoyer M (eds) Sustainable agriculture reviews, vol 14. Springer, Cham, pp 345–447
FAO (2007) Global assessment of land degradation and improvement GLADA report 5. Rome, Italy
Feliciano D, Ledo A, Hillier J, Nayak DR (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254:117–129
Fisher MW (2007) Shelter and welfare of pastoral animals in New Zealand. N Z J Agric Res 50: 347–359
Forde DC (1937) Land and labour in a Cross River village. Geogr J X:1
Galindo J (2004) Efecto de metabolitos secundarios de especies vegetales arbóreas y arbustivas en la población microbiana ruminal de animales. Proyecto Optimización de la fermentación microbiana ruminal mediante el empleo de técnicas manipuladoras. Programa Biotecnología Agrícola. CITMA. La Habana
Gashaw T, Bantider A, Silassie H (2014) Land degradation in Ethiopia: causes, impacts and rehabilitation techniques. J Environ Earth Sci 4:98–104
Giller KE, Beare MH, Lavelle P, Izac AMN, Swift MJ (1997) Agricultural intensification, soil biodiversity and agroecosystem function. Appl Soil Ecol 6(1):3–16
Giraldo C, Escobar F, Chará JD, Calle Z (2011) The adoption of silvopastoral systems promotes the recovery of ecological processes regulated by dung beetles in the Colombian Andes: ecological processes regulated by dung beetles. Insect Conserv Diversity 4(2):115–122

Gold MA, Garrett HE (2009) Agroforestry nomenclature, concepts, and practices. In: Garrett HE (ed) ASA, CSSA, and SSSA books. American Society of Agronomy and Soil Science Society of America, Madison, pp 45–56
Gordon AM, Naresh RPF, Thevathasan V (2005) How much carbon can be stored in Canadian agroecosystems using a silvopastoral approach? In: Mosquera-Losada MR, Rigueiro-Rodríguez A, McAdam J (eds) Silvopastoralism and sustainable land management. CABI, Wallingford, pp 210–218
Grace J, San-Jose J, Meir P, Miranda H, Montes R (2006) Productivity and carbon fluxes of tropical savannas. J Biogeogr 33:387–400
Gupta RK, Kumar V, Sharma KR, Buttar TS, Singh G, Mir G (2017) Carbon sequestration potential through agroforestry: a review. Int J Curr Microbiol App Sci 6(8):211–220
Gupta SR, Dagar JC, Teketay D (2020) Agroforestry for rehabilitation of degraded landscapes: achieving livelihood and environmental security. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore, pp 23–68
Gurian-Sherman D (2011) Raising the stakes. Global warming and pasture-raised beef production in the United States. Union of Concerned Scientists, Cambridge
Harvey CA, Komar O, Chazdon R, Ferguson BG, Finegan B, Griffith DM, Martínez-Ramos M, Morales H, Nigh R, Soto-Pinto L, Van Breugel M, Wishnie M (2008) Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot: conservation plans for tropical rural landscapes. Conserv Biol 22:8–15
Haynes RJ, Mokolobate MS (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutr Cycl Agroecosyst 59(1):47–63
Heaton L, Fullen MA, Bhattacharyya R (2016) Critical analysis of the van Bemmelen conversion factor used to convert soil organic matter data to soil organic carbon data: comparative analyses in a UK loamy sand soil. Espaço Aberto 6(1):35–44
Henry B, Murphy BW, Cowie AL (2019) Sustainable land management for environmental benefits and food security. A synthesis report for the GEF
Hewins DB, Lyseng MP, Schoderbek DF, Alexander M, Willms WD, Carlyle CN, Chang SX, Bork EW (2018) Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Sci Rep 8(1):1336
Houghton RA, Nassikas AA (2018) Negative emissions from stopping deforestation and forest degradation, globally. Glob Chang Biol 24(1):350–359
Hu WL, Liu JX, Ye JA, Wu YM, Guo YQ (2005) Effect of tea saponin on rumen fermentation in vitro. Anim Feed Sci Technol 120(3):333–339
Ibrahim M, Guerra L, Casasola F, Neely N (2010) Importance of silvopastoral systems for mitigation of climate change and harnessing of environmental benefits. In: Abberton M, Conant R, Batello C (eds) Grassland carbon sequestration: management, policy and economics. Proceedings of the workshop on the role of grassland carbon sequestration in the mitigation of climate change. Integrated Crop Management, Vol. 11. FAO, Rome, Italy
Imo M (2009) Interactions amongst trees and crops in taungya systems of wester Kenya. Agrofor Syst 76:265–273
IPCC (2006) Guidelines for national greenhouse gas inventories, vol 5. Institute for Global Environmental Strategies, Hayama, p 66
Ispikoudis I, Sioliou KM (2005) Cultural aspects of silvopastoral systems. In: Mosquera-Losada MR, Rigueiro-Rodríguez A, McAdam J (eds) Silvopastoralism and sustainable land management. CABI, Wallingford, pp 319–323
Johnson DL, Lewis LA (2007) Land degradation: creation and destruction. Lanham, Rowman and Littlefield, p 303
Jose S, Bardhan S (2012) Agroforestry for biomass production and carbon sequestration: an overview. Agrofor Syst 86:105–111
Jose S, Dollinger J (2019) Silvopasture: a sustainable livestock production system. Agrofor Syst 93(1):1–9

Jose S, Walter D, Mohan Kumar B (2017) Ecological considerations in sustainable silvopasture design and management. Agrofor Syst 93:317–331

Kabir M, Webb EL (2007) Can homegardens conserve biodiversity in Bangladesh? Biotropica 40(1):95–103

Kamwenda G (2002) Ngitili agrosilvipastoral systems in the United Republic of Tanzania. Unasylva 53(4):46–50

Karlen DL, Ditzler CA, Andrews SS (2003) Soil quality: why and how? Geoderma 114(3–4): 145–156

Keogh ME, Törnqvist TE (2019) Measuring rates of present-day relative sea-level rise in low-elevation coastal zones: a critical evaluation. Ocean Sci 15(1):61–73

Kumari C, Gupta SR, Dagar JC, Singh V, Kumar M (2018) Carbon sequestration and microbial biodiversity in saline water irrigated agroforestry systems of semiarid hyperthermic Camborthids regions of North-West India. J Soil Salinity Water Q 10(2):133–148

Kumawat RN, Misra AK, Louhaichi M (2014) Managing rangelands: promoting sustainable tree species “Prosopis cineraria”: a wonder tree for agroforestry in arid and semi-arid areas. https://repo.mel.cgiar.org/handle/20.500.11766/4

Kunst C, Navall M, Ledesma R, Silberman J, Anríquez A, Coria D, Bravo S, Gómez A, Albanesi A, Grasso D, Nuñez JAD, González A, Tomsic P, Godoy J (2016) Silvopastoral systems in the Western Chaco Region, Argentina. In: Peri PL, Dube F, Varella A (eds) Silvopastoral systems in Southern South America, vol 11. Springer, Cham, pp 63–87

Kuzyakov Y, Schleuss P, Miehe G, Heitkamp F, Sebeer E, Spielvogel S, Xu X, Guggenberger G (2016) Mechanisms of soil degradation and consequences for carbon stocks on Tibetan grasslands. Geophys Res Abstr 18:11813

Lacorte SM, Barth SR, Colcombet L, Crechi EH, Esquivel JI, Fassola HE, Goldfarb MC, Pezzuti R, Videla D, Winck RA (2016) Silvopastoral systems developed in misiones and corrientes, Argentina. In: Peri P, Dube F, Varella A (eds) Silvopastoral systems in Southern South America, vol 11. Springer, Cham

Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustain For 7(5):5875–5895

Le Quéré C, Andrew RM, Friedlingstein P, Sitch S, Pongratz J, Manning AC, Korsbakken JI, Peters GP, Canadell JG, Jackson RB, Boden TA, Tans PP, Andrews OD, Arora VK, Bakker DCE, Barbero L, Becker M, Betts RA, Bopp L, Zhu D (2018) Global carbon budget 2017. Earth Syst Sci Data 10(1):405–448

Lefroy FC, Dann PR, Wildin JH, Wesley-Smith RN, McGowan AA (1992) Trees and shrubs as sources of fodder in Australia. Agrofor Syst 20:117–139

Lin KC, Hamburg SP, Wang L, Duh CT, Huang CM, Chang CT, Lin TC (2017) Impacts of increasing typhoons on the structure and function of a subtropical forest: reflections of a changing climate. Sci Rep 7(1):4911

Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agron Sustain Dev 34(2):443–454

Ludwig JA (2005) Disturbances and landscapes: the little things count. In: Wiens JA, Moss MR (eds) Issues and perspectives in landscape ecology, 1st edn. Cambridge University Press, Cambridge, pp 42–51

Ma H, Ju H (2007) Status and trends in land degradation in Asia. In: Sivakumar MVK, Ndiangui N (eds) Climate and land degradation. Springer, Berlin, pp 55–64

Maathai W (2012) Agroforestry, climate change and habitat protection. In: Nair PKR, Garrity D (eds) Agroforestry—the future of global land use, vol 9. Springer, Cham, pp 3–6

Mangalassery S, Dayal D, Meena SL, Ram B (2014) Carbon sequestration in agroforestry and pasture systems in arid northwestern India. Curr Sci 107(8):1290–1293

Mas AH, Dietsch TV (2004) Linking shade coffee certification to biodiversity conservation: butterflies and birds in Chiapas, Mexico. Ecol Appl 14(3):642–654

Mead D (2009) Biophysical interactions in silvopastoral systems: a New Zealand perspective. In: Actas del 1° Congreso Nacional de Sistemas Silvopastoriles, pp 14–16

Mead DJ, Millner J, Smail PW (1999) Farm forestry and shelter. In: New Zealand pasture and crop science. Springer, Oxford, pp 269–291
Millennium Ecosystem Assessment (2005) Ecosystems and human well-being, synthesis. Island Press, Washington, p 155
Mohamed E, Belal AA, Ali RR, Saleh A, Hendawy EA (2019) Land degradation. In: El-Ramady H, Alshaal T, Bakr N, Elbana T, Mohamed E, Belal AA (eds) The soils of Egypt. Springer, Cham, pp 159–174
Montagnini F, Nair PKR (2004) Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agrofor Syst 61(1):281–295
Montagnini F, Ibrahim M, Murgueitio E (2013) Silvopastoral systems and climate change mitigation in Latin America. Bois For Trop 316:3–16
Moreno G, Franca A, Pinto Correia MT, Godinho S (2014) Multifunctionality and dynamics of silvopastoral systems. Options Méditer Ser A 109:421–436
Moumen A, Azizi G, Chekroun KB, Baghour M (2016) The effects of livestock methane emission on the global warming: a review. Int J Glob Warm 9(2):229
Mupeyo B, Barry TN, Pomroy WE (2011) Effects of feeding willow (*Salix* spp.) upon death of established parasites and parasite fecundity. Anim Feed Sci Technol 164:8–20
Murgueitio E, Chará JD, Solarte AJ, Uribe F, Zapata C, Rivera JE (2013) Agroforestería Pecuaria y Sistemas Silvopastoriles Intensivos (SSPi) para la adaptación ganadera al cambio climático con sostenibilidad. Rev Colombiana Cien Pecuarias 26:313–316
Naeth MA, Bailey AW, Pluth DJ, Chanasyk D, Hardin RT (1991) Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. J Range Manage Arch 44(1):7–12
Nair PKR (2012) Carbon sequestration studies in agroforestry systems: a reality-check. Agrofor Syst 86:243–253
Nair PKR (2014) Agroforestry: practices and systems. In: Encyclopedia of agriculture and food systems. Elsevier, Amsterdam, pp 270–282
Nair PKR (2015) Silvopastoral systems in Southern South America. Springer, Cham, pp 7–8
Nair PKR, Fernandes ECM, Wambugu PN (1984) Multipurpose leguminous trees and shrubs for agroforestry. Agrofor Syst 2:145–163
Nair PKR, Buresh RJ, Mugendi DN, Latt CR (1999) Nutrient cycling in tropical agroforestry systems: myths and science. In: Buck LE, Lassoie JP, Fernandes ECM (eds) Agroforestry in sustainable agricultural systems. CRC Press, Boca Raton, pp 1–31
Nair PKR, Kumar BM, Nair VD (2021) An introduction to agroforestry: four decades of scientific developments, 2nd edn. Springer, Cham
Nguyen TM, Binh DV, Ørskov ER (2005) Effect of foliages containing condensed tannins and on gastrointestinal parasites. Anim Feed Sci Technol 121(1–2):77–87
Odhiambo HO, Ong CK, Deans JD, Wilson J, Khan AAH, Sprent JI (2001) Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. Plant Soil 235: 221–233
Oenema O, Bannink A, Sommer SG, Van Groenigen JW, Velthof GL (2008) Gaseous nitrogen emissions from livestock farming systems. In: Nitrogen in the environment. Elsevier, Amsterdam, pp 395–441
Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmi S (2016) Greenhouse gas emissions from soils—a review. Geochemistry 76(3):327–352
Olsson L, Barbosa H, Bhadwal S, Cowie A, Delusca K, Flores-Renteria D, Hermans K, Jobbagy E, Kurz W, Li D, Sonwa DJ, Stringer L (2019) Land degradation. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
Ong CK, Kho RM (2015) A framework for quantifying the various effects of tree-crop interactions. In: Ong CK, Black CR, Wilson J (eds) Tree-crop interactions: agroforestry in a changing climate, 2nd edn. CABI, Wallingford, pp 1–23

Ortiz J, Dube F, Neira P, Panichini M, Stolpe NB, Zagal E, Martínez-Hernández PA (2020) Soil quality changes within a (*Nothofagus obliqua*) forest under silvopastoral management in the Andes Mountain Range. Sustainability 12(17):6815

Osei AK, Kimaro AA, Peak D, Gillespie AW, Van Rees KCJ (2017) Soil carbon stocks in planted woodlots and Ngitili systems in Shinyanga, Tanzania. Agrofor Syst 92:251–262

Öztürk M, Altay V, Güvensen A (2019) Sustainable use of halophytic taxa as food and fodder: an important genetic resource in southwest Asia. In: Hasanuzzaman M, Nahar K, Öztürk M (eds) Ecophysiology, abiotic stress responses and utilization of halophytes. Springer, Singapore, pp 235–257

Pachauri RK (2012) Climate change and agroforestry. In: Nair PK, Garrity D (eds) Agroforestry—the future of global land use, vol 9. Springer, Cham, pp 13–15

Peri PL, Banegas N, Gasparri I, Carranza CH, Rossner B, Pastur GM, Cavallero L, López DR, Loto D, Fernández P, Powel P, Ledesma M, Pedraza R, Albanesi A, Bahamonde H, Eclesia RP, Piñeiro G (2017) Carbon sequestration in temperate silvopastoral systems, Argentina. In: Montagnini F (ed) Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty, vol 12. Springer, Cham, pp 453–478

Pitta DW, Barry TN, Lopez-Villalobos N, Kemp PD (2005) Effects on ewe reproduction of grazing willow fodder blocks during drought. Anim Feed Sci Technol 120(3–4):217–234

Prasad JVNS, Srinivas K, Rao CS, Ramesh C, Venkatravamma K, Venkateswarlu B (2012) Biomass productivity and carbon stocks of farm forestry and agroforestry systems of leucaena and eucalyptus in Andhra Pradesh, India. Curr Sci 103:536–540

Priano ME, Fusé VS, Mestelan S, Berkovic AM, Guzmán SA, Gratton R, Juliarena MP (2017) Afforested sites in a temperate grassland region: influence on soil properties and methane uptake. Agrofor Syst 92:311–320

Priano ME, De Bernardi M, Fernández ME, Gyenge JE, Juliarena MP (2020) Los suelos forestales y su rol en la remoción del metano atmosférico. Instituto Nacional de Tecnologia Agropecuaria (INTA), New York, pp 1–3

Ramírez-Restrepo CA, Pernthaner A, Barry TN, López-Villalobos N, Shaw RJ, Pomroy WE, Hein WR (2010) Characterization of immune responses against gastrointestinal nematodes in weaned lambs grazing willow fodder blocks. Anim Feed Sci Technol 155(2–4):99–110

Reeder JD, Schuman GE (2002) Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environ Pollut 116(3):457–463

Rees RM, Bingham IJ, Baddeley JA, Watson CA (2005) The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. Geoderma 128(1–2): 130–154

Rigueiro-Rodríguez A, Fernández-Núñez E, González-Hernández P, McAdam JH, Mosquera-Losada MR (2008) Agroforestry systems in Europe: productive, ecological and social perspectives. In: Rigueiro-Rodróguez A, McAdam J, Mosquera-Losada MR (eds) Agroforestry in Europe, vol 6. Springer, Cham, pp 43–65

Rochette P, Chantigny MH, Ziadi N, Angers DA, Bélanger G, Charbonneau É, Pellerin D, Liang C, Bertrand N (2014) Soil nitrous oxide emissions after deposition of dairy cow excreta in Eastern Canada. J Environ Qual 43(3):829–841

Saarijärvi K, Rukajarvi P (2009) Nitrogen dynamics of cattle dung and urine patches on intensively managed boreal pasture. J Agric Sci 147(4):479–491

Sala OE (2000) Global biodiversity scenarios for the year 2100. Science 287(5459):1770–1774

Sales-Baptista E, Ferraz-de-Oliveira MI (2021) Grazing in silvopastoral systems: multiple solutions for diversified benefits. Agrofor Syst 95(1):1–6

Sarvade S, Upadhyay VB, Agrawal SB (2019) Quality fodder production through silvo-pastoral system: a review. In: Dev I, Ram A, Kumar N, Singh R, Kumar D, Uthappa AR, Handa AK, Chaturvedi OP (eds) Agroforestry for climate resilience and rural livelihood. Scientific Publishers, Jodhpur, pp 345–359

Schmidt A, Alonso M (2016) Manejo silvopastoril de los bosques de ñirre en la XII Región de Magallanes. Informe Final Proyecto Fondo de Investigación en Bosque Nativo CONAF Código 029/2013, Santiago

Schuur EAG, McGuire AD, Schädel C, Grosse G, Harden JW, Hayes DJ, Hugelius G, Koven CD, Kuhry P, Lawrence DM, Natali SM, Olefeldt D, Romanovsky VE, Schaefer K, Turetsky MR, Treat CC, Vonk JE (2015) Climate change and the permafrost carbon feedback. Nature 520(7546):171–179

Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agrofor Syst 60(2):123–130

Sharrow SH, Brauer D, Clason TR (2015) Silvopastoral practices. In: Garrett HE (ed) ASA, CSSA, and SSSA books. American Society of Agronomy and Soil Science Society of America, Madison, pp 105–131

Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11(4):368. https://doi.org/10.3390/f11040368

Singh G, Dagar JC (2005) Greening sodic lands: Bichhian model. Technical Bulletin No. 2/2005. Central Soil Salinity Research Institute, Karnal, p 51

Skiba UM, Rees RM (2014) Nitrous oxide, climate change and agriculture. CAB Rev 9:10

Smith KA (2017) Changing views of nitrous oxide emissions from agricultural soil: Key controlling processes and assessment at different spatial scales: N_2O emissions from agricultural soil. Eur J Soil Sci 68:137–155

Sokol NW, Kuebbing-Sara E, Karlsen-Ayala E, Bradford MA (2019) Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. New Phytol 221(1):233–246

Sollins P, Homann P, Caldwell BA (1996) Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma 74(1–2):65–105

Soni ML, Subbulakshmi V, Yadava ND, Tewari JC, Dagar JC (2016) Silvopastoral agroforestry systems: lifeline for dry regions. In: Dagar JC, Tewari JC (eds) Agroforestry research developments. Nova Publishers, New York, pp 245–305

Spaan W, Bodnár F, Idoe O, de Graaff J (2004) Implementation of contour vegetation barriers under farmer conditions in Burkina Faso and Mali. Quart J Int Agric 43(1):21–38

Steinfeld H (ed) (2006) Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations, Rome

Stocking M, Murnaghan N (2000) Land degradation—guideline for field assessment. Overseas Development Group, University of East Anglia, Norwich

Stocking MA, Murnaghan N (2001) A handbook for the field assessment of land degradation. Routledge, London, p 169

Syakila A, Kroeze C (2011) The global nitrous oxide budget revisited. GHG Measure Manage 1(1):17–26

Tewari VP, Singh M (2006) Tree-crop interaction in the Thar Desert of Rajasthan (India). Sécheresse 17:326–332

Thevathasan NV, Coleman B, Zabek L, Ward T, Gordon AM (2018) Agroforestry in Canada and its role in farming systems. In: Gordon AM, Newman SM, Coleman BRW (eds) Temperate agroforestry systems, 2nd edn. CABI, Wallingford, pp 7–49

Thiombiano L, Tourino-Soto I (2007) Status and trends in land degradation in Africa. In: Sivakumar MVK, Ndiangui N (eds) Climate and land degradation. Springer, Berlin, pp 39–53

Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, Hölscher D, Juhrbandt J, Kessler M, Perfecto I, Scherber C, Schroth G, Veldkamp E, Wanger TC (2011) Multifunctional shade-tree management in tropical agroforestry landscapes - a review: multifunctional shade-tree management. J Appl Ecol 48(3):619–629

Udawatta RP, Jose S (2011) Carbon sequestration potential of agroforestry practices in temperate North America. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems, vol 8. Springer, Cham, pp 17–42

UNEP (2016) Unlocking the sustainable potential of land resources: evaluation systems, strategies and tools. A report of the Working Group on Land and Soils of the International Resource Panel
Upson MA, Burgess PJ, Morison JIL (2016) Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture. Geoderma 283:10–20
Uscola M, Villar-Salvador P, Oliet J, Warren CR (2014) Foliar absorption and root translocation of nitrogen from different chemical forms in seedlings of two Mediterranean trees. Environ Exp Bot 104:34–43
USDA (ed) (2014) Soil survey staff: keys to soil taxonomy, 12th edn. USDA-Natural Resources Conservation Service, Washington
Valipour A, Plieninger T, Shakeri Z, Ghazanfari H, Namiranian M, Lexer MJ (2014) Traditional silvopastoral managementand its effects on forest stand structure in northern Zagros, Iran. For Ecol Manag 327:221–230
Van Noordwijk M, Roshetko JM, Murniati AMD, Suyanto FC, Tomich TP (2008) Farmer tree planting barriers to sustainable forest management. In: Snelder DJ, Lasco RD (eds) Smallholder tree growing for rural development and environmental services, vol 5. Springer, Cham, pp 429–451
Vandermeulen S, Ramírez-Restrepo CA, Marche C, Decruyenaere V, Beckers Y, Bindelle J (2018) Behaviour and browse species selectivity of heifers grazing in a temperate silvopastoral system. Agrofor Syst 92(3):705–716
Vitousek PM (1997) Human domination of earth's ecosystems. Science 277(5325):494–499
Wall DH, Bardgett RD, Covich AP, Snelgrove PV (2004) The need for understanding how biodiversity and ecosystem functioning affect ecosystem services in soils and sediments
Wang Z, Hoffmann T, Six J, Kaplan JO, Govers G, Doetterl S, Van Oost K (2017) Human-induced erosion has offset one-third of carbon emissions from land cover change. Nat Clim Chang 7(5): 345–349
Webb NP, Marshall NA, Stringer LC, Reed MS, Chappell A, Herrick JE (2017) Land degradation and climate change: building climate resilience in agriculture. Front Ecol Environ 15(8): 450–459
WRB (2006) IUSS Working Group: world reference base for soil resources 2006 - A framework for international classification, correlation and communication. Food and Agriculture Organization of the United Nations, Rome
Zabel F, Putzenlechner B, Mauser W (2014) Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PLoS ONE 9(9):e107522
Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6(1):29987

Chapter 8
Utilization of Saline and Other Poor-Quality Waters to Sustain Agroforestry Production

R. K. Yadav, Raj Kumar, Awtar Singh, and Jagdish Chander Dagar

Abstract Saline and poor-quality water irrigation-induced land degradation constitutes a major threat to the agricultural productivity. Agroforestry systems prove more beneficial than conventional arable agriculture systems in areas where saline and other categories of poor-quality water are the only source of irrigation. Poor-quality water use in forestry and agroforestry plantations can provide large number of ecosystems services, such as carbon sequestration, lowering surface temperature, regulate fresh water flows, control erosion, and maintain soil fertility. Available evidences suggest that tree species such as *Acacia nilotica*, *Eucalyptus tereticornis*, and *Prosopis juliflora* are found highly effective in terms of growth and biomass production under saline irrigation. Various tree species and crops can be grown in different agroforestry systems, such as agri-silviculture system, silvopastoral system, agri-horti system, multipurpose woodlots, and saline aquaforestry. Biodrainage and phytoremediation techniques could be highly effective in recycling and reusing the saline and poor-quality water and reducing soil contamination due to salts and other pollutants. Even a business model can be developed to use and recycle wastewater for afforestation programs along with the production of pulpwood, fuelwood, and timber-wood. However, several constraints and challenges exist in the use of saline and poor-quality water for plantation programs and these must be addressed for obtaining the greater ecological and environmental benefits of investments. Overall, agroforestry and tree plantations seem to be ecologically and economically viable options to judiciously use saline and the poor-quality water for enhancing land productivity and protecting the soil and water resources.

Keywords Saline irrigation · Poor-quality water · Saline agroforestry · Afforestation · Biodrainage · Phytoremediation · Wastewater · Sewage

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8.1 Introduction

Salinity, in situ as well as arising due to poor-quality water irrigations, adversely affects growth and biomass production of the plant species (Singh 2009). Every year increase in salinization is degrading productive agriculture land into unproductive one, leading to a major threat to the global food and livelihood security (Zhang 2014; Bhardwaj et al. 2019). Salinization negatively affects plant structure and functions because of alteration in the soil properties and water availability to plants (Gentili et al. 2018). The continuous use of poor-quality saline water for irrigation leads to the development of salinity in the soils (Yadav et al. 2007). The saline water mostly contains Na^+, K^+, Ca^{2+}, and Mg^{2+} cations, and Cl^- and SO_4^{2-} anions, and the increased ions concentration leads to the high electrical conductivity (EC) of the water (Zhang et al. 2006). The long-term application of saline water for irrigation causes the ion toxicity, osmotic stress, nutrient imbalance and deficiency, water stress, and unfavorable soil structure (Yadav et al. 2020). This results in the ion homeostasis and nutrient imbalance causing alteration in various physiological and biochemical processes in the plant species (Guo et al. 2010; Yadav et al. 2020). The high salinity stress reduces stomatal conductance, transpiration, photosynthesis, number of leaves and branches, and leaf area of different plant species (Rahneshan et al. 2018; Neha et al. 2022).

Salinization causes alteration of the physiological and biochemical traits of the exposed plant, resulting in reduction in the crop productivity and deterioration of precious land resources. Therefore, reduction in agricultural productivity, as a consequence of salinization, promotes the interest of growing salt-tolerant tree plantation for increasing the sustainability, productivity, and profitability from the salinity-afflicted landscapes (Dagar and Minhas 2016a, b; Minhas et al. 2020; Kumar et al. 2021). Based on salt tolerance, the tree species can be categorized as sensitive, moderately tolerant, highly tolerant, and extremely high tolerant (Tomar et al. 2003; Dagar 2014). Once saline irrigation is given to tree species, it may moderately affect tree species; however, overall effects on tree growth are lower compared to the agricultural crops. Moreover, different EC levels of irrigation water could have varied effect on the structure and functional attributes of tree species (Banyal et al. 2017); therefore, it is important to document the available literature and information about the possibility, scope, and challenges of using saline water in irrigating the tree species suitable for agroforestry. Further, many salt-tolerant arable crops like barley and mustard compatible with fruit trees like karonda (*Carissa carandas*), Bael (*Aegle marmelos*), and goose berry (*Emblica officinalis*) with saline irrigation (ECiw 8–10 dS m^{-1}); forage grasses such as *Panicum laevifolium*, *P. maximum*, *P. coloratum*, *P. virgatum*, *Leptochloa fusca*, *Brachiaria mutica*, and many others; some aromatic and medicinal plants such as cultivars of lemon grass (*Cymbopogon flexuosus* cv OD-58, RRL-16), *Matricaria chamomilla*, *Plantago ovata*, *Adhatoda vasica*, *Aloe vera*, *Cassia senna*, *Lepidium sativum*, and *Catharanthus roseus* are found suitable for cultivation with saline irrigation in agroforestry mode or as sole crops without having any significant adverse effects on soil properties (Dagar 2003, 2014, 2018; Dagar et al. 2016b; Dagar and Minhas 2016a, b). Therefore, agroforestry is a practicable option to utilize the saline and other poor-quality waters to sustain the agricultural production. Some of the studies conducted on judicious utilization of saline water in biosaline agroforestry have been discussed in this chapter.

8.2 Categories of Salty Water

The water used for irrigation purposes always contains some salts; however, nature and ionic composition of salts vary due to several factors. The composition, concentration, and ratios of different cations and or anions determine the quality of irrigation water. Accordingly, the criteria for appraisal of quality irrigation water include (a) total concentration of soluble salts which determine its salinity; (b) ratio of sodium to other cations, which determine sodicity/alkalinity; (c) anionic composition of water mainly concentration of CO_3^{2-} and HCO_3^- with relation to concentration of basic cations (Ca^{2+} and Mg^{2+}); and (d) concentration of fluoride, boron, selenium, or any other ions which are toxic to plant growth even at small concentration. Apart from this, Na^+, Cl^-, and HCO_3^- also create specific ion toxicities in some cases. Based on SAR and EC of irrigation water, various classifications have been proposed for evaluation of irrigation water quality, but none of them is uniformly applicable across all the conditions. However, most common classification (Table 8.1), which is acceptable at global level has been outlined by United States Salinity Laboratory (Richards 1954).

Table 8.1 Classification of saline water as per United States Salinity Laboratory

Salinity hazard classes	EC (mS m^{-1})	Remarks	Sodium hazard classes	SAR	Remarks
C_1 (Low salinity)	0–25	Suitable for irrigation	S_1 (low sodium hazards)	0–10	Negligible sodicity hazards to soil
C_2 (Medium salinity)	25–75		S_2 (medium sodium hazards)	10–18	Appreciable hazards to soil, however it can be utilized for irrigation with appropriate management
C_3 (High salinity)	75–225	Not suitable for irrigation	S_3 (high sodium hazards)	18–26	Can cause appreciable build-up of ESP in soil, hence, unsuitable for irrigation
C_4 (very high salinity)	225–500		S_4 (very high sodium hazards)	>26	

Table 8.2 Guidelines for utilization of saline irrigation waters (RSC <2.5 me L^{-1})

Soil texture (% clay)	Crop tolerance	Upper limits of EC (dS m^{-1}) in irrigation water under different rainfall region (cm)		
		<35	35–55	55–75
Fine (>30)	S	1.0	1.0	1.5
	ST	1.5	2.0	3.0
	T	2.0	3.0	4.5
Moderately fine (20–30)	S	1.5	2.0	2.5
	ST	2.0	3.0	4.5
	T	4.0	6.0	8.0
Moderately coarse (10–20)	S	2.0	2.5	3.0
	ST	4.0	6.0	8.0
	T	6.0	8.0	10.0
Coarse	S	-	3.0	3.0
	ST	6.0	7.5	9.0
	T	8.0	10.0	12.5

S, ST, and T designated as sensitive, semi-tolerant and tolerant crops to EC content of irrigation water

$$SAR = Na^+/\left[\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}\right])$$

Further, sodicity/alkalinity of irrigation water is also determined with residual sodium carbonate [RSC (Eaton 1950)]. The RSC of irrigation water is estimated through following equation:

$$RSC = (CO_3{}^{2-} + HCO_3{}^{-}) - (Ca^{2+} + Mg^{2+})$$

where concentration of $CO_3{}^{2-}$, $HCO_3{}^{-}$, Ca^{2+}, and Mg^{2+} are represented in me L^{-1}.

Concept of RSC, for deciding the suitability of irrigation water, is most commonly used in south Asian countries including India. Sodium adsorption ration (SAR) and Adjusted SAR (Adj. R_{Na}) is another parameter, as proposed by Suarez (1981), for assessing of sodicity hazards in irrigation water. Adj. RNa is calculated using following equations:

$$adj.RNa = Na^+/[\sqrt{(Cax + Mg^{2+})/2}]$$

Here, exchangeable calcium (Cax) represents adjusted value of Ca^{2+} based on EC and $HCO_3{}^{-}$: Ca^{2+} ratios.

In India, after conducting several experiments, at ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal; Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar, and Punjab Agricultural University (PAU) Ludhiana, these institutes have jointly developed water quality guidelines in 1990 as described in Tables 8.2 and 8.3 (Minhas and Gupta 1992).

Table 8.3 Guidelines for utilization of sodic irrigation waters (RSC >2.5 me L^{-1} and EC of irrigation water <4.0 dS m^{-1})

Soil texture (% clay)	Limits of		Remarks
	SAR (me L^{-1})$^{1/2}$	RSC (me L^{-1})	
Fine (>30)	10	2.5–3.5	When the irrigation water containing Na <75%, (Ca + Mg <25%) and rainfall is >55 cm, the upper limit of the RAC range are safe
Moderately fine (20–30)	10	3.5–5.0	
Moderately coarse (10–20)	15	5.0–7.5	
Coarse (<10)	20	7.5–10.0	

Note: Criteria of soil texture are applicable for soil layer up to depth of 1.5 m, (b) where ground water table comes within 1.5 m, at any time and when hard pan (subsoil) layer is found in the root zone, the limits need shifting to the next finer textural class)

8.3 Use of Saline Water in Agroforestry

8.3.1 Scope of Using Saline Water in Agroforestry

In order to address the issue of global climate change and land degradation neutrality, the agroforestry has become the most significant part of land-use planning and management. In the majority of water-scarce/low-rainfall areas, the poor-quality (saline and sodic) water is available in the underground aquifers. Pumping water out from these aquifers for irrigation in agriculture causes salinity and sodicity buildup, as well as other environmental problems. Several approaches have been suggested and adopted to regulate the use of low-quality water for irrigating crops to obtain higher crop yield and minimize salt accumulation. However, the environmental costs continue to constrain in their efficient utilization; consequently, use of saline water for trees and agroforestry has emerged as an alternative measure for recycling the saline water and halting the land degradation (Minhas and Dagar 2016). Further, agroforestry systems have become more beneficial over conventional agricultural systems in areas where poor-quality water is the only source of irrigation. Moreover, practicing agroforestry in salinity-afflicted landscapes can provide large number of social, economic, and environmental benefits to the society (Fig. 8.1).

8.3.2 Saline Water Irrigation for Trees

Saline groundwater may be utilized to establish salt-tolerant tree plantations on normal as well as degraded arid and semi-arid saline soils. Hence, it can contribute in enhancing the productivity and profitability of even resource-poor lands. The

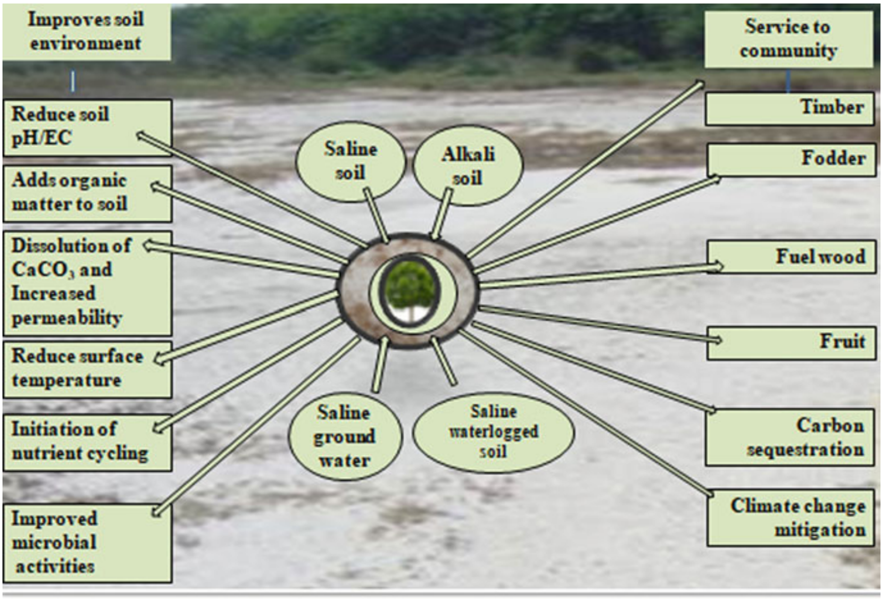

Fig. 8.1 Potential benefits of agroforestry in saline lands

information on establishment of trees and their subsequent growth under saline irrigation is mainly available from the Indian subcontinent (Dagar and Minhas 2016a, b). Trees such as *Azadirechta indica*, *Acacia nilotica*, *A*, *ampliceps*, *A. stenophylla*, *Eucalyptus camaldulensis*, *E. tereticornis*, *Casuarina equisetifolia*, *C. glauca*, *C. obesa*, *Tamarix articulata*, *T. indica*, *T. stricta*, *Prosopis cineraria*, *P. juliflora*, *P. alba*, *Leucaena leucocephala*, *Salvadora persica*, *S. oleoides* along with many *Atriplex* species have been reported to hold potential on sandy strata and could successfully be utilized for revegetation of desert land using water from saline aquifers (ECiw 4–18 dS m^{-1}) and also sea water after dilution (Qureshi et al. 1993a, b; Ahmad and Ismail 1993; Weissbein et al. 2008; Ismail et al. 2019). Some tree species have a high potential for achieving acceptable growth and biomass output under saline water irrigation (Minhas 1996; Dagar and Minhas 2016a, b).

Tomar et al. (2003) observed that species such as *Acacia tortilis*, *Acacia nilotica*, *Prosopis juliflora*, *Eucalyptus tereticornis*, *Tamarix articulata*, and *Cassia siamea* have good potential to grow and produce satisfactory biomass when irrigated with saline water of ECiw 8.5–10 dS m^{-1} for the first 3 years (Fig. 8.2). When provided with supplemental saline irrigation, the *Crescentia alata*, *Samanea saman*, and *Terminalia arjuna* showed good early growth and survival, but found sensitive once irrigation was discontinued. A rank index was developed based on survival, growth, and biomass production of different tree species. Among the 31 species tested, *Acacia nilotica*, *Eucalyptus tereticornis*, and *Prosopis juliflora* were placed

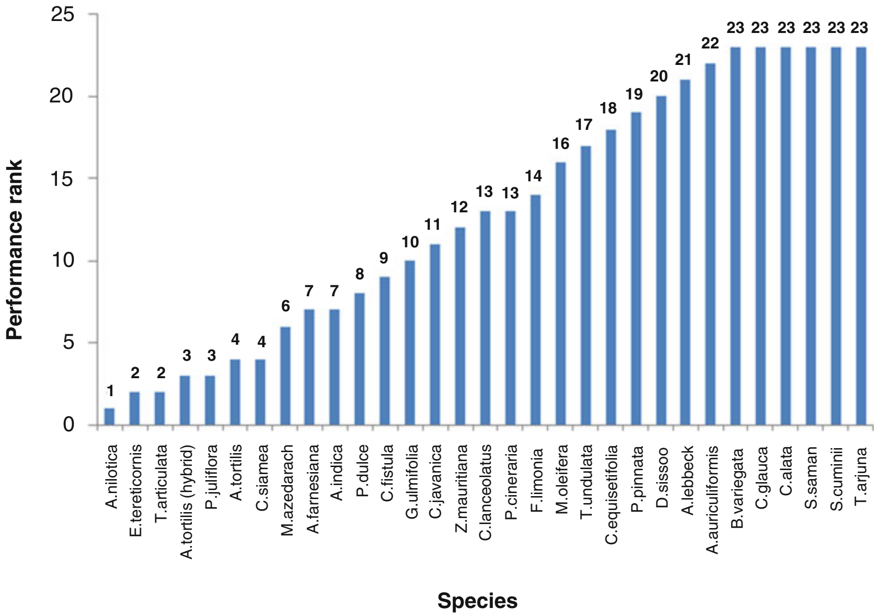

Fig. 8.2 Ranking (1: highest; 23: lowest) of tree species based on performance under saline irrigation. Trees include*: Acacia auriculiformis*, *Acacia farnesiana*, *Acacia nilotica*, Acacia *tortilis*, Acacia *tortilis* (hybrid), *Albizia lebbeck*, *Azadirachta indica*, *Bauhinia variegata*, *Callistemon lanceolatus*, *Cassia fistula*, *Cassia glauca*, *Cassia javanica*, *Cassia siamea*, *Casuarina equesitifolia*, *Crescentia alata*, *Dalbergia sissoo*, *Eucalyptus tereticornis*, *Feronia limonia*, *Guazuma ulmifolia*, *Melia azedarach*, *Moringa oleifera*, *Pithecellobium dulce*, *Pongamia pinnata*, *Prosopis cineraria*, *Prosopis juliflora*, *Samanea saman*, *Syzygium cuminii*, *Tamarix articulata*, *Tecomella undulata*, *Terminalia arjuna*, *Ziziphus mauritiana*. Source: Tomar et al. (2003)

first, second, and third in the ranking order, respectively, followed by others (Fig. 8.2).

Banyal et al. (2017) investigated the potential for growing *Melia composita* on salty soils using saline irrigation. They observed that the trees of *Melia* can grow well under saline water irrigation (ECiw up to 12 dS m^{-1}) regimes. However, it was also revealed that the decrease in growth performance was proportionate to increase in salinity of irrigation water. Irrigation with low salinity water resulted in the improved growth of tree plantation and reduced soil salinity. The fruit tree species such as *Feronia limonia*, *Ziziphus mauritiana*, *Carissa carandas*, *Emblica officinalis*, and *Aegle marmelos* could be cultivated with saline water irrigation of EC up to 10 dS m^{-1} (Dagar et al. 2016b). The details of the suitability of various tree species for saline irrigation as reported by different workers are presented in Table 8.4.

Table 8.4 Suitability of tree and some shrub species for saline irrigation as reported by different authors

Species	Saline irrigation (EC dS m^{-1})	Reference
Azadirachta indica	4–15	Ahmad et al. (1985)
Proposis juliflora, *Acacia nilotica*, *Terminalia arjuna*, *Syzygium cuminii*, *Albizia lebbeck*, *Pongamia pinnata*, *Cassia auriculata*, *Cassia siamea*	4–6	Chaturvedi (1985)
Proposis juliflora, *Tamarix articulata*	8	Jain et al. (1983)
Eucalyptus hybrid, *Leucaena leucocephala*	6	
Azadirachta indica, *Casuarina equisetifolia*, *Eucalayptus camaldulensis*	15	Ahmad et al. (1987)
Proposis juliflora, *Tamarix articulata*	20–30	
Proposis cineraria, *P. juliflora*, *Tamarix articulata*, *T. indica*, *T. stricta*, *Acacia nilotica*, *Salvadora persica*, *S. oleoides*, *Leucaena leucocephala*	4–18	Qureshi et al. (1993a, b)
Tamarix articulata, *Acacia modesta*, *A. nilotica*, *Prosopis chilensis*, *P. siliquastrum*, *P. alba*	10–20	Hussain and Gul (1993)
Acacia nilotica, *Eucalyptus tereticornis*, *Prosopis juliflora*	8–10	Tomar et al. (2003)
Olea cuspidata	2–8	Wiesman et al. (2004)
Pistacia atlantica, *P. terebinthus*	<6	Kamiab et al. (2012)
Phoenix dactylifera, *Achras zapota*, *Grewia asiatica*, *Ziziphus mauritiana*	8–10	Ahmad et al. (1987)
Carissa carandas, *Aegle marmelos*, *Emblica officinalis*, *Ziziphus mauritiana*, *Feronia limonia*	10	Dagar et al. (2008, 2016)
Salicornia bigelovii, *Terminalia catappa*, *Pandanus* spp., *Suaeda mosquinii*, *Batis maritima*, *Crithmum maritimum*, *Zygophyllum album*, *Nitraria sibirica*, *Suaeda salsa*, *Chenopodium glaucum*, *Descurainia sophia*	Moderate to high salinity	Glenn et al. (1991), Dagar et al. (2005), Weber et al. (2001), Marcone (2003), Zarrouk et al. (2003), Yajun et al. (2003)

8.3.3 Irrigation Management in Agroforestry Trees

In the past, the trees were usually not irrigated in India due to the greater cost and lack of availability of the resources. But, with the advent of short rotation forestry and development of forest-based industries, the provision of irrigation of tree species has become significant to produce the desired economic output within the shorter period. In arid and semi-arid areas, the irrigation practice becomes even more important aiming to enhance the productivity and profitability of land, especially from the degraded landscapes. Irrigation is particularly important during the initial stages of plantation establishment, growth, and development. Irrigation should be applied at least once in 7 days in first 3 months and then once in a month for at least 1 year depending upon the distribution and frequency of rainfall. Use of saline water in mixed or cyclic mode with the good-quality water has shown potential for achieving the greater impact of plantations and investments. The frequency of irrigation depends upon the type of plant species, regional climate, and soil conditions. But there is a lack of information about the saline irrigation schedule for most of the tree species. In general, the frequency of irrigation may be more in shallow pits than deeper pits. Spot irrigation is more useful than flood irrigation during the first year of planting. In the later stages, irrigation is needed to be done through channels joining the pits.

8.3.4 Agroforestry System Suitability Under Saline Irrigation

The various combinations of tree and crops can be grown to use the saline water and even reclaim the degraded salt-affected soils, and same has been discussed below.

8.3.4.1 Agri-silviculture System (Tees and/or Arable Crops)

Agri-silviculture is the practice of growing timber and fuelwood species and/or other useful trees with crops and other vegetables in a specific spatial and temporal arrangement. In the alley space, multipurpose trees (MPTs) are grown alongside the agricultural crops. Agri-silviculture offers enormous potential of using saline water for growing trees and cultivating arable crops with them. Many agricultural crops, such as Egyptian clover (*Trifolium alexandrinum*), rice, wheat, and mustard could be grown successfully under *Populus deltoides*, *E. tereticornis*, and *A. nilotica* and these decreased the soil pH and EC of alkali soil during 5-year period (Singh et al. 2011). Biswas and Biswas (2014) also suggested that the trees such as *Albizia lebbeck*, *Terminalia arjuna*, and *Prosopis juliflora* can be cultivated alongside indigenous agricultural crops in saline conditions. Banyal et al. (2017) demonstrated that intercrops such as pearl millet and mustard can be productively grown in association with *Eucalyptus tereticornis* and *Melia composita* using the saline water for irrigation in saline soils. Many crops such as pearl millet, mustard, cluster bean, *Eruca sativa*, and barley can successfully be grown as agroforestry crops in dry regions having saline aquifers. Psyllium (*Plantago ovata* var JI-4, Sel-10), a food and medicinal crop could be successfully cultivated with saline water (EC 10 dS m^{-1}) with trees like *Acacia nilotica*, *A. tortilis*, *Tamarix articulata*, and *Feronia limonia* (Tomar et al. 2010). Many under-explored high value or medicinal crops such as castor (*Ricinus communis*), lemon grass (*Cymbopogon flexuosus*), *Catharanthus roseus*, *Lepidium sativum*, *Cassia senna*, dill (*Anethum graveolens*), *Eruca sativa*, *Matricaria recutita* syn *M. chamomilla*, *Euphorbia antisyphalitica*, and many others could be cultivated successfully in isolation and with trees irrigating with saline water ranging from EC 4.5 to 10.0 dS m^{-1} (Dagar et al. 2005, 2006, 2008, 2012, 2013, 2019, 2020a, b). For more details, see review by Dagar (2018).

A perennial halophytic grass *Distichlis palmeri*, used for making biscuits and bread from its grains and another highly nutritive grain producing crop Quinoa (*Chenopodium quinoa*), performs well in hypersaline conditions and can be grown with water of sea salinity (Pearlsteina et al. 2012; Adolf et al. 2013; Ismail et al. 2019). Quinova can be grown under coconut, *Terminalia catappa*, *Pongamia pinnata*, *Casuarina glauca*, and species of *Pandanus* in coastal areas. Many coastal plants found growing along beaches and mangroves and associate species are consumed as food. These have potential for their domestication as agroforestry crops. Species such as *Zostera marina*, *Chenopodium album*, *Salicornia bigelovii*, *Diptotaxis tenuifolia*, and many others have been established as food crops and may be developed as agroforestry crops with coastal tree species. These can be explored commercially using sea water for irrigation. At least 50 species of seed-bearing halophytes are potential sources of edible oil and proteins (Dagar 2018). *Salicornia bigelovii*, *Terminalia catappa*, *Suaeda moquinii*, *Kosteletzkya virginica*, *Batis maritima*, *Chenopodium glaucum*, *Crithmum maritimum*, and *Zygophyllum album* are a few examples.

8.3.4.2 Silvopastoral System (Trees + Grasses)

In this system, trees, fodder, and domesticated animals are all integrated in a mutually beneficial manner. It is a unique type of agroforestry practice based on controlled grazing principles. To recover alkali soils, promising salt-tolerant MPTs, such as *P. juliflora*, *A. nilotica*, *Casuarina equisetifolia*, *Terminalia arjuna*, *Tamarix articulata*, and *Pongamia pinnata* combined with various grass species such as *Leptochloa fusca*, *Chloris gayana*, *Brachiaria mutica*, and *Sporobolus spp*. can be grown in an agroforestry system in salt-affected soils. Numerous grasses such as *Leptochloa fusca*, *Aeluropus lagopoides* and species of *Eragrostis*, *Sporobolus*, *Chloris*, *Panicum*, and *Brachiaria* can successfully be cultivated with different trees in waterlogged saline regions with salt-tolerant trees to create viable and sustainable silvopastoral systems that support the animal husbandry (Dagar 2014). *Aeluropus lagopoides*, *Sporobolus helvolus*, *Cynodon dactylon*, *Brachiaria ramosa*, *Paspalum spp.*, *Echinochloa colona*, *E. crusgalli*, *Dichanthium annulatum*, *Vetiveria zizanioides*, and *Eragrostis* species are important grasses that are resistant of both salinity and water stagnation and may be cultivated effectively in silvopastoral systems. Species of *Ziziphus*, *Suaeda*, *Kochia*, *Salsola*, *Atriplex*, *Salvadora*, and *Haloxylon* are prominent forage shrubs found in high salinity areas and grazed by sheep, goat, and camel (Dagar 2014, 2018). Further, *P. juliflora* and *L. fusca*-based and *A. nilotica* and *Chloris gayana*-based silvopastoral systems are considered quite efficient in reclaiming sodic soils by decreasing the soil EC and pH and increasing soil nutrients (Singh et al. 2014, 2022).

In a long-term experiment conducted on highly sodic soil [pH > 10.6, ESP 89] in the Indo-Gangetic plains, Singh et al. (2022) reported that in a silvopastoral system with 10 years old plantation of *Acacia nilotica*, *Casuarina equisetifolia* and *Eucalyptus tereticornis* fodder grass species viz. *Chloris gayana*, *Panicum maximum*, and *Pennisetum purpureum* performed well. The maximum biomass production of understory grasses was recorded from *A nilotica* + *C. gayana* system, while the highest nutritive value in terms of N, P, K, and crude protein content (%) was recorded in *A. nilotica* + *P. purpureum*. A strong correlation between photosynthetically active radiation (PAR) and understory grasses was observed. Significantly higher tree growth and biomass yield were recorded under silvopastoral systems over silvicultural system. A significant reduction in soil bulk density and increase in soil porosity, infiltration rate, and water holding capacity (WHC) were recorded in silvopastoral systems over silviculture and control due to reduced sodicity, addition of leaf litter, increase in microbial activities due to tree and grassroots, better plant growth, and fine root decay. Reduction in soil pH, exchangeable sodium percent (ESP), and increase in soil organic carbon were more pronounced under silvopastoral systems over the silviculture. The highest reduction in these parameters was recorded under the *A. nilotica* + *C. gayana* system. Similarly, soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), and dehydrogenase activities were also higher under silvopastoral systems. The highest MBC was recorded in *C. equisetifolia* + *C. gayana* which was 302.8% higher than the control. However, highest MBN and dehydrogenase activities were recorded under *A. nilotica* + *C. gayana* system. Hence, on the basis of total biomass yield and improvement in soil bio-physicochemical properties, *A. nilotica* + *C. gayana* system was highly ameliorative and productive system for the restoration of degraded sodic soils. Therefore, a huge opportunity exists to develop silvopastoral system in areas endowed with high salinity or sodicity and having saline groundwater as source of irrigation.

Halophytes have been used as forage in arid and semi-arid parts of the world for millennia. A large number of salt-tolerant species have been incorporated in pasture improvement programs across the globe. Among trees, species of *Acacia (ampliceps*, *bivenosa*, *cyclopes*, *eburnea*, *holosericea*, *leucophloea*, *nilotica*, *salicina*, *saligna*, *senegal*, *tortilis*, *victoria)*, *Prosopis (alba*, *chilensis*, *cineraria*, *glandulosa*, *juliflora*, *pallida*, *tamarugo)*, and *Leucaena leucocephala* are widely cultivated in isolation or as agroforestry tree on field boundary or a constituent of silvopastoral system including using saline water (Dagar 2014, 2018). Among other trees grown on salt-affected lands and with saline irrigation, used as forage for cattle, goats, sheep, and camel include *Ailanthus excelsa*, *Anogeissus pendula*, *Azadirachta indica*, *Balanites roxburghii*, *Calophospermum mopane*, *Cordia rothii*, *Dalbergia sissoo*, *Dichrostachys cinerea*, *Ficus* spp., *Parkinsonia aculeata*, *Pithecellobium dulce*, *Salvadora persica*, *S. oleoides*, and *Ziziphus* spp. Among shrubs, saltbushes (species of *Atriplex*) are common throughout the Middle East region while *Haloxylon persicum*, *H. salicornicum*, *Kochia indica*, and *Ziziphus nummularia* are common Indian forages of saline silvopastoral systems (Dagar 2018).

8.3.4.3 Agri-Horti System (Fruit Trees + Arable Crops)

Most of the fruit species are sensitive to salts; however, some salt-tolerant species could be cultivated successfully in the salt-affected soils and also with saline irrigation. Fruit tree species such as *Ziziphus mauritiana*, *Emblica officinalis*, *Achras zapota*, *Psidium guajava*, *Carissa carandas*, *Aegle marmelos*, *Punica granatum*, *Sygygium cuminii*, and *Tamarindus indica* are considered to be salt-tolerant and could be grown in soils containing moderate salts (Rahneshan et al. 2018; Dagar et al. 2008, 2016a, b). Numerous fruit-based saline agroforestry models have been developed and are widely implemented by the rural communities. For instance, the systems comprised of Bael (*Aegle marmelos*), Goose berry (*Emblica officinalis*), and Karonda (*Carrisa carandas*) as tree components and cluster bean (in rainy season) and barley and mustard (in winter) as subsidiary components have been found to be practicable and economically viable when irrigated with waters containing salinity ranging from moderate (ECiw 4–5.8 dS m^{-1}) to high (ECiw 8.2–10.5 dS m^{-1}) (Dagar et al. 2008, 2016b). Establishment of fruit trees in these conditions can result in overall improvements in the soil quality and the microclimate (Sharma et al. 2015). Therefore, fruit-based system using saline irrigation, preferably microirrigation method can successfully be developed to enhance the farm income and restore the salt-affected soils.

8.3.4.4 Multipurpose Woodlots

Woodlots are cultivated for a variety of objectives, including timber, fodder, soil protection, soil amelioration, etc. Salt-resistant multipurpose trees (MPTs) are grown in a block plantation with the close spacing. This practice ameliorates saline soil by improving the physical, chemical, and biological properties as well as produces biomass for industrial purpose. Evidences have shown that improvement in soil organic carbon by 3–5 times and reduction in soil pH from 10.3 to 8.03 was observed under a 20-year-old tree plantation (Singh et al. 1993). *P. juliflora* is one of the potential MPTs for reclaiming saline-sodic areas as it significantly decreases the ECe and ESP and increases organic carbon (percent) in comparison to land without trees (Biswas and Biswas 2014). Tree species such as *Tamarix articulata* and *Acacia nilotica* are also found to lower the soil pH and ESP with simultaneous increase in OC in the top layer by 0.23% (Dagar et al. 2001). The tree species such as *A. nilotica*, *Albizia procera*, *L. leucocephala*, *Azadirachta indica*, and *Eucalyptus tereticornis* were also identified to be the best suited tree species for alkali soil rehabilitation (Khan and Shukla 2003). Moreover, MPTs could be best suited to use saline water for enhancing the productivity of salinity-afflicted landscape (Dagar et al. 2001, 2008; Dagar 2014). *Casuarina equisetifolia* and *Eucalyptus camaldulensis* are also cultivated as woodlots. The attention has also been paid towards commercial woodlots yielding biodiesel such as *Jatropha curcas*, *Pongamia pinnata*, and *Ricinus* *communis* and these plantations can be raised using saline irrigation (Dagar and Minhas 2016b).

In coastal areas, people prefer to raise commercial plantations in saline areas and establish plantations with saline irrigation. Woodlots of *Casuarina spp*., *Thespesia populnea*, *Calophyllum inophyllum*, *Pongamia pinnata*, *Lannea coromandelica*, *Bambusa bambos*, and *Borassus flabellifer* are commonly grown (Dagar and Minhas 2016a). These species along with *Tamarindus indica* and *Azadirechta indica* are also planted as boundary trees.

8.3.4.5 Saline Aquaforestry (Trees + Fish)

In this system, the various fish-favored salt-resistant plants and shrubs are introduced on the boundary and in surrounding of fish ponds. Fish uses tree leaves as a feed ingredient. The primary functions of this system are fish production and bund stabilization. Shrimp and fish farming can help to reclaim degraded land and use poor-quality water resources. Inland saline aquaculture is common in high salinity areas of Asia, Australia, Israel, and the United States (Allan et al. 2009). Agroforestry trees can be cultivated around the pond's periphery to meet the farmer's legitimate demands for fuelwood, small timber, and fodder. For example, *Eucalyptus* could be planted effectively on the pond bunds, and it will assist to keep the seepage and surface soil salinity under control. Broad bed furrow system is widely used in coastal areas of India cultivating crops in between beds and trees (e.g., *Moringa oleifera*, banana, *Casuarina*, *Morinda citrifolia*, coconut) on raised beds in wider spaces and vegetables between the trees and fish in the channels (Dagar and Minhas 2016a; Dagar et al. 2020a). However, such combinations have yet to be properly researched, but they will be beneficial to the economic survival of farms in saline ecosystems.

8.3.5 Biodrainage

Biodrainage is defined as the lowering of ground water table by planting fast growing trees with high transpiration rate (Dagar et al. 2016a; Singh and Lal 2018). Generally, high water table and saline groundwater are the peculiar characteristics of saline soils. The establishment of vegetation is difficult due to presence of toxic ions and poor aeration in the root zone. However, some species are able to grow under waterlogged saline conditions. For example, *Eucalyptus* is the principal species, which has a strong growth potential in the waterlogged moderately saline soils. A large number of other species have good potential to grow and tolerate saline waterlogged conditions. The major species have been categorized in three classes, (1) fast biodrainers: *Eucalyptus hybrid*, *Eucalyptus tereticornis C-10*, *Eucalyptus tereticornis C-130*, *Acacia ampliceps*, and *Prosopis juliflora*; (2) medium biodrainers: *Eucalyptus tereticornis C-3*, *Callistemon lanceolatus*, and *Melia* *azedarach*; and (3) slow biodrainers: *Terminalia arjuna* and *Pongamia pinnata* (Dagar 2014). Eucalyptus has been found most successful and profitable in lowering down of water table and increasing farm income when grown in wider spaces along with arable crops like rice and wheat (Ram et al. 2011; Dagar et al. 2016a). In coastal areas, *Casuarina junghuhniana*, *C. equisetifolia*, *C. glauca*, *Acacia mangium*, and *Eucalyptus tereticornis* have been found promising with field crops (Roy Chowdhury et al. 2011; Jena et al. 2011; Dagar et al. 2020a). Aquaculture intervention was also introduced successfully in these fields after digging out standard ponds and introducing air-breathing fish (*Clarias batrachus* and *Anabas testudineus*) and banana varieties and the enterprise was quite profitable.

8.3.5.1 Planning and Designing Biodrainage

The primary requirement for planning the biodrainage plantation is the catchment water balance and precise identification of the recharge and discharge areas. The following points need to be considered for establishing a biodrainage model for controlling salinization and rising water table in any area (Singh and Lal 2014; Minhas et al. 2020):

- *Water balance*: The excess use of irrigation water to crops cause an increase in the groundwater table, resulting in the development of water logging situation. The plantation of high-water transpiration capacity trees like *Eucalyptus* is needed which could transpire excess soil water into the atmosphere. This could help in combating the problem of water logging in the root zone.
- *Area for plantation*: The area under biodrainage plantation should be such that the amount of evapotranspiration should be equal to the total annual recharge. This could prevent the water logging situation. If area under plantation is either less or more, then lesser or more water will be removed which could make biodrainage plantation ineffective.
- *Salt tolerance*: Tree species selected for biodrainage should have good tolerance to salts, because waterlogged soils mostly contain salts, that could hamper tree growth and biomass production, which is prerequisite for establishing a biodrainage system.
- *Drawdown of water table*: Trees should have a high transpiration rate to lower down the water table beneath and in surrounding area.
- *Salt balance*: Biodrainage plantation should lower not only the water table but also the soil salinity of the area.
- *Economic aspects*: The species considered for biodrainage should have high economic value so that investment made in establishing and managing plantation could be recovered from the sale of tree products. Biodrainage plantations also provide other indirect environmental and ecological benefits to the stakeholders. For a successful model, see Dagar et al. (2016a).

8.3.5.2 Establishment of Plantations

Plantation for biodrainage can be either block plantation or ridge plantation. For block plantation, depending upon area, a number of trees can be decided based on the species and direction along the bunds of waterlogged agricultural fields. Ridge-to-ridge distance can be kept 50–60 m and the ridge should be at least 2–3 m wide at base, 2 m at top and 0.5 m in height. For example, two rows of genetically superior clonal plants of *Eucalyptus tereticornis* (Mysore gum) can be planted at a spacing of 1×1 m on the top of ridge at ridge-to-ridge distance of about 65 m resulting in a density of 300 plants per ha. The total area under strip-plantation of *Eucalyptus tereticornis* works out to be 4% of each ha (390 m^2 ha^{-1}) and rest of the 96% area is available for agricultural crops; thus, it becomes an agroforestry model of biodrainage (Ram et al. 2011; Dagar et al. 2016a).

8.3.5.3 Performance of Trees Under Biodrainage

The biodrainage block plantations of *Eucalyptus tereticornis* at the Indira Gandhi Nahar Pariyojana (IGNP) site in Rajasthan and Dhob-Bhali research plot in Haryana in India was found quite promising in reclamation of waterlogged areas (Ram et al. 2008). The transect of trees such as *Eucalyptus tereticornis*, *E. camaldulensis*, *Acacia nilotica*, *Populus deltoides*, *Prosopis juliflora*, *Casuarina equisetifolia*, *Pongamia pinnata*, *Terminalia arjuna*, *Syzygium cuminii*, *Dalbergia sissoo*, etc. successfully checked seepage and helped in controlling waterlogging. In another study, Bala et al. (2014) conducted an experiment to remove excess water from the land through biodrainage in a waterlogged area in Indian desert. They observed that the plantation of *Eucalyptus camaldulensis*, *E. fastigata*, *E. rudis*, and *Corymbia tesselloris* on raised bunds lowered the ground water table considerably. The performance of *E. rudis* was best in term of growth, biomass production, transpiration rate, and overall biodrainage potential. They reported that the groundwater level receded by 145 cm in *E. rudis* plot compared to 90 cm, 70 cm, and 60 cm in *C. tessellaris*, *E. camaldulensis*, and *E. fastigata*, respectively, within a period of 5 years. Dagar et al. (2016a) evaluated the impact of three planting spacings viz. 1×1 m, 1×2 m, and 1×3 m of *Eucalyptus tereticornis* in waterlogged saline soils. Due to high transpiration rate of *Eucalyptus*, the water table was lowered by 43.0 cm, 38.5 cm, and 31.5 cm in respective spacing than in adjacent fields without plantation during the fourth year of plantation. The results suggested that in a rotation of 6 years, closer spacing of 1×1 m under strip plantation of Eucalyptus in paired rows was the optimum for achieving higher water table drawdown, wood biomass production, carbon sequestration, and crop productivity in waterlogged fields.

8.4 Sewage and Industrial Wastewater

8.4.1 Present Status of Wastewater and Its Use

In India, about 61.75 billion liters of sewage and 0.5 billion liters of industrial wastewater are generated per day with installed sewage treatment capacity of only about 21.96 billion liter per day only (Roy 2020). Industries include iron rolling mills, textiles industries, cement, industrial gases, chemicals, plastics, electronics, electrical, and mineral-based industries use dyes, chemicals, and other materials to impart desired strength and quality to the products (Singh 2018). These industries process a variety of chemicals ranging from enzymes to detergents, dyes to soda, or acids to salts or their suspended or aqueous form and generate wastewater containing large amounts of dyes, chemical substances, and heavy metals (Ladia et al. 2015; Singh 2018). The disposal of wastewater is the most important water-polluting source causing health hazards to animal and human beings (Ilyas et al. 2019).

Economic utilization of wastewater varies through land-based practices and is a popular option for removal, nutrient recycling, and water utilization across the world (Monteverdi et al. 2014). Use of domestic wastewater for irrigation includes large number of benefits of safe and low-cost treatment of wastewater, conservation, and recharge of groundwater reserves after phytoremediation by plants and use of nutrients present in wastewater for productive purposes. Total concentration and kind of salts determines the quality of water for irrigation and latter may vary in both kind and degree, depending on type of soil, climate, and crop. The presence of nutrient elements and organic matter in wastewater can improve the soil properties and tree growth as well as biomass. However, the presence of heavy metals, toxic ions, and microbes limits the utilization of wastewater for agricultural use (Singh and Bhati 2005).

8.4.2 Using Wastewater for Forest Plantation

Sewage farming is cultivating the forest tree species for multipurposes with wastewater, which can overcome the issue of health-associated hazards (Thawale et al. 2006). Using wastewater in forestry consists of reusing the water and promoting the nutrient recycling. This approach can meet the irrigation requirement of plantations and help to increase forest cover and provide large number of ecological and environmental benefits as well as filter the wastewater to reduce the treatment costs. It can also help in developing green urban forest in cities under wastewater irrigation, which can significantly contribute in restoring the ecological balance and improving the ecosystem services through sustainable use of wastewater. However, wastewater-irrigated forestry plantations also pose some challenges, such as safety issues, which cannot be undermined and need to be addressed. However, ability of different species to grow in wastewater-contaminated soils and utilize the treated/ untreated wastewater effectively depends on phytoremediation ability, growth pattern and biomass partitioning, changes in root metabolism, capacities to accumulate the minerals and salts, and most importantly the adaptability of the species to the toxicants (Kidd et al. 2015; Maaloul et al. 2019). Wastewater-irrigation and use in forestry and agroforestry plantation provides large number of ecosystems services, such as carbon sequestration, lowering surface temperature, regulate fresh water flows, control erosion, and maintain soil fertility. In water scare arid and desert lands, the wastewater could be promoted for ecological restoration of degraded landscape. If economics is taken into consideration, then wastewater reuse in forestry may not be as viable as agriculture; however, benefits could be much higher if we consider the economics of ecological and environmental services and values provided by the trees.

8.4.3 Criteria for Selection of Trees Species

The criteria for selection of tree for afforestation program depend on the climate, soil, market availability, and wastewater type, quality, and quantity (Vertessy et al. 2000). Several other criteria were suggested to identify and select tree species for afforestation program using the wastewater irrigation (Yadav et al. 2016) include:

- Tree species should be fast growing with high biomass production. The tree product should be easily sold in the local market.
- Tree species should be multipurpose in nature to cater the demand of firewood, timber, food, fodder, fiber, edible or nonedible oils, medicinal products, paper pulp, ability to fix atmospheric nitrogen, etc.
- Tolerance to soil conditions like soil reaction, salinity, heavy metal toxicity, pathogen, and excess water.
- Well adapted to various climate-related factors, such as temperature, rainfall, frost, and wind speed, especially to the extreme weather events.
- Tree species should have a good potential of high carbon sequestration to reduce the climate change effects.
- Capacity to improve physical, chemical, and biological properties of soils through addition of organic matter and creation of better microclimatic conditions.
- Tree should be preferably evergreen so that it could consume and transpire maximum amount of wastewater.

8.4.4 Phytoremediation Mechanisms Involved in Using Wastewater

Tree plantations are often expected to use water at higher rates than the shorter vegetation. The greater aerodynamic roughness of tree plantations, large canopy, greater biomass, and deeper rooting system allows extraction of water down from the deep soils. There are a number of ways by which certain plant species, together with the organisms in their rhizosphere soil, are able to cleanse their environment (Paulo

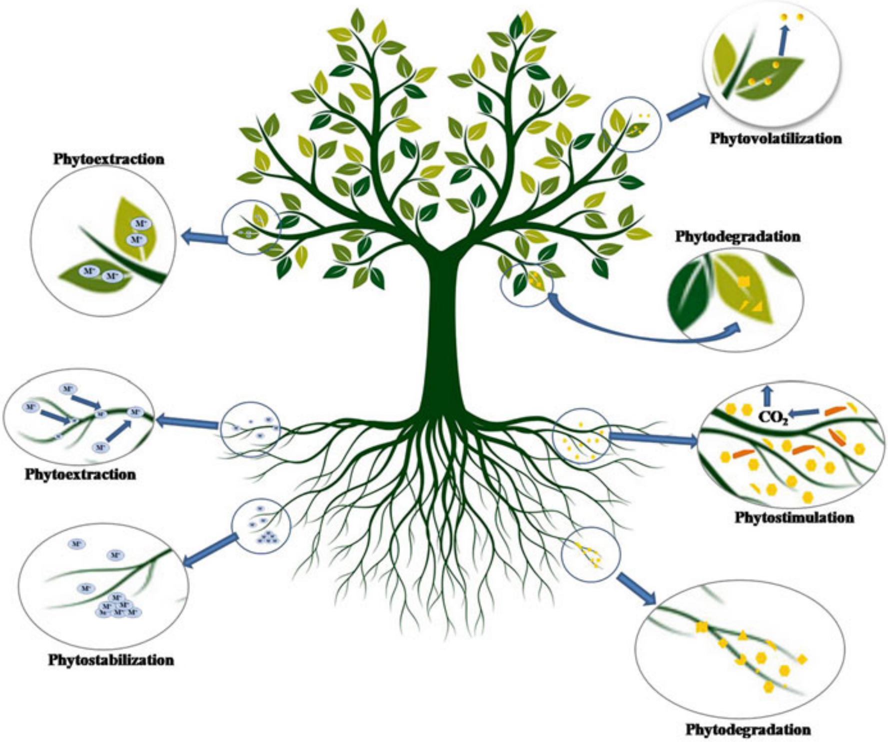

Fig. 8.3 Schematic representation of phytoremediation strategies (adapted from Paulo et al. 2014)

et al. 2014). The different physico-biochemical processes, such as phytostabilization (locking up toxicant), phytoextraction (removal and destruction of toxicant), phytodegradation (bacteria break down toxicant and convert into less toxic substances), phytovolatilization (conversion of toxic substances into less toxic gases), translocation (reduction of toxicity), and stabilization (fixation of metals in roots followed by bacterial breakdown), exist in the plant species which reduce the toxicity caused by the heavy metals and ions (Fig. 8.3).

The agroforestry systems composed of high water transpiring trees with high-rate transpiration systems (HRTS) are the land management practice based upon the transpiration capacity of tree species which uses the treated wastewater (Minhas et al. 2015). In the process of wastewater irrigation, the solid waste material is filtered on the top soil layers, enabling the water-laden heavy metal and ions to infiltrate into the deeper soil layers. Once water and heavy metal come in contact with the tree roots, both are absorbed and transported to the various plant parts. The transpiration process allows water to transpire into the atmosphere, while metals and toxic ions are accumulated in the vegetative parts. In this process, the metal and toxic ions are stored in plant body and the transpired clean water recycled to land surface through rainfall. Additional advantage of the tree plantations would be the harvest of large quantity of metals, as trees are known to tolerate and accumulate greater levels of these toxic metals (Heuperman et al. 2002). The only disadvantage with trees is low tolerance limit of certain species to toxic ions, and above the threshold limit these could die. It may lead to the failure of the plantations. The solid waste material filtered on top soil surface could be recycled to produce various industrial products. It can be interpreted that the wastewater application to tree plantation reduces the soil and water pollution due to metal and ions toxicity and thus increases the fresh water availability for the other remunerative major activities.

8.4.5 Performance of Tree Species

The response of tree species to wastewater irrigation varies with the species, growth rate, and age of the plantation. However, the physiological mechanism underlying plays major role in providing tolerance to toxicity caused by the heavy metals and ions. The findings of an experiment showed that *Acacia nilotica*, *Azadirechta indica*, *Prosopis juliflora*, and *Tamarix aphylla* performed better with increased irrigation level, whereas *Eucalyptus camaldulensis*, *Salvadora persica*, *S. oleoides*, and *Tacomella undulata* species require additional nutrients added through treated wastewater. *A. nilotica*, *E. camaldulensis*, *P. juliflora*, and *A. indica* were observed to be best species for achieving the greater growth and biomass and for utilizing the wastewater. Such techniques can be applied in urban forestry to reduce the waste generation and improve the soil and water quality. Moreover, tree species differed in their preferences to increased quantity of irrigation water and nutrients added through wastewater application (Singh et al. 2021). The use of wastewater in urban and peri-urban agroforestry has been dealt in detail in Chap. 4 in this publication by Dagar et al. (2023).

8.4.6 FAO Experience in North Africa

FAO has been promoting the use of treated wastewater to irrigate forests and trees since the 90s in various countries of North Africa. In Algeria, constructed wetlands were used to filter wastewater for irrigating the trees. Irrigating trees with treated wastewater improve soil properties, health, and conditions of agriculture through enhancement of incomes and food security of regional population. In addition, using treated wastewater for irrigation reduces the burden on freshwater and improve the water quality and pollution in the area FAO (2008).

8.4.7 Developing Business Models for Using Wastewater

8.4.7.1 Basic Business Model for Wastewater Treatment and Utilization

A business model as suggested by Drechsel and Hanjra (2018) can be developed to use and recycle wastewater for afforestation program along with the production of pulpwood, fuelwood, and timber. This process reduces the risk and threats involved with the discharge of wastewater and sludge, and create businesses for government authorities which can treat wastewater and utilize it for the economic purpose. Both the public and private sector can setup treatment plant for recycling wastewater through irrigation application to the forest plantation. The treatment plant needed to be located at a place where land is available for agriculture, forestry, or landscaping activities. Different institutional models can be adopted depending upon the regional administrative and public procedures (Drechsel and Hanjra 2018). The two common examples are: (1) both the wastewater treatment plant, water transport, and agriculture/forestry activities are managed by the same company; and (2) each wastewater treatment plant, water transport, and recycling are shared by the different companies (Fig. 8.4).

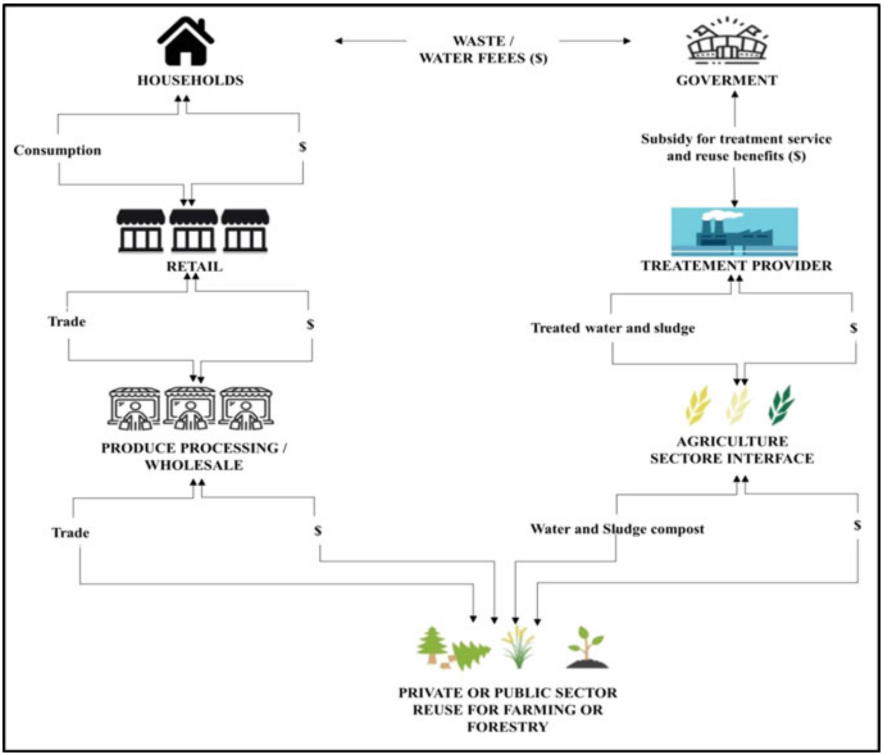

Fig. 8.4 A conceptual framework for developing a wastewater-based business model (adapted from Drechsel and Hanjra 2018)

These companies can be either public- or government-owned enterprises. In the second case, the treatment plant sells water and nutrient-rich sludge, e.g., to a water user company for the forestry/BUSINESS MODEL VALUE CHAIN agriculture sector. The wastewater treatment plant generates its revenue from the households (sanitation fees), government subsidies, and from the sale of treated wastewater to forestry sector. The business model is extremely useful for controlling soil and water pollution and improving forest-induced regional ecosystem services through prevention of wastewater and sludge discharge.

8.4.7.2 Case Study of Wastewater Business Model of Drarga, Morocco

The wastewater treatment plant in the town of Drarga, Morocco, has been set up with a business model geared to generating revenue through a reuse system which produces tertiary treated water, reed grass, and sludge-based co-compost for sale. In this system, the household is charged some sanitation fees, which is spent to meet the operational cost recovery. This model eliminates land and water pollution, which arises from the disposal of wastewater. The treatment plant was developed through a multistakeholder agreement of the commune with government providing land for construction and facilitating the administrative and legal procedures. The wastewater was recycled and treated to WHO standards, making it suitable for irrigating the agriculture and forest plantation. The treated water is sold to farmers who lack the irrigation and other infrastructure resources, and the treated wastewater guaranteeing them a year-round water supply.

8.4.7.3 Planning Wastewater Use in Agroforestry

Planning tree-wastewater-use systems requires both agroforestry and engineering expertise; however, USDA (2000) suggested the following considerations for using wastewater in irrigating forest trees (Fig. 8.5):

Effluent quantity and quality: Detailed information about the qualitative and quantitative characteristics of the effluent to be treated is needed to decide the nature and extent of the plantation. Quantity and quality often vary depending on the waste inputs, water supply, treatment process, and type of storage/retention facility.

Irrigation requirement and nutrient loading rates: The water and nutrient requirements of the trees determine the land area to be put under plantation. The water requirement of trees can be worked out from the available literature or from the expert advice. The nutrient requirement of tree species could also be found from the subject matter specialist and from the available literature on the identified species.

Water delivery system: The water delivery system generally includes pumps and pipelines needed to transport recycled and treated wastewater from the treatment plant through irrigation tanks and pipelines to the plantation site. The sizing and design criteria vary according to: (1) quantity of reuse water and required delivery

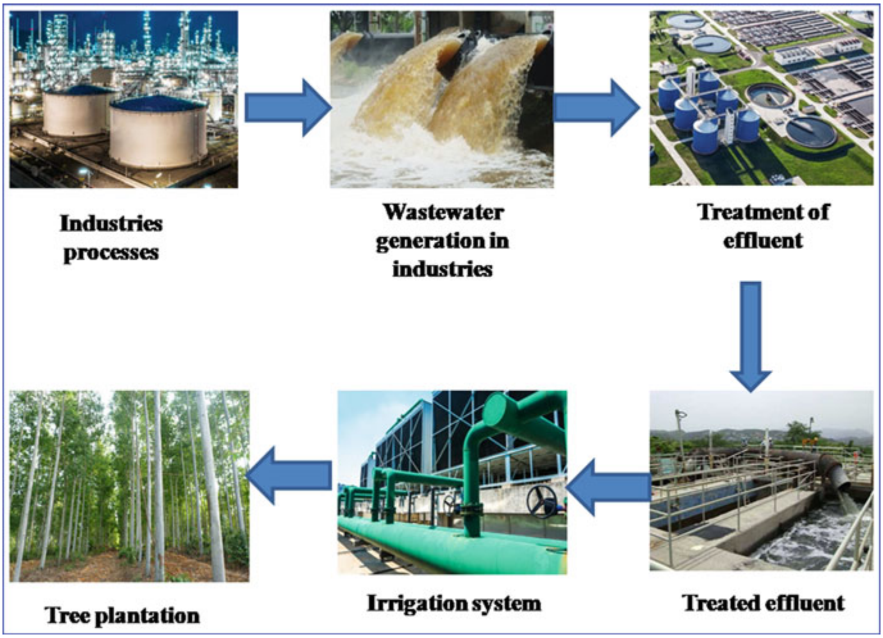

Fig. 8.5 Utilization of wastewater for agroforestry (adapted from Kalaiselvi et al. 2019)

pressure, (2) peak daily irrigation rate, and (3) distance and elevation between the wastewater treatment facility and the irrigation system.

Irrigation system: For planning the proper irrigation system components and layout, several factors are needed to identify the: (1) tree-to-tree distance, (2) soil infiltration capacity, (3) effluent water quality and filtration desires, and 4) overall management and operations requirement of the plantation.

Operation and maintenance: Operation and maintenance considerations include: (1) performance of sprinkler, (2) timing of filtration cycle, (3) pump flows and pressures, (4) record of total application rates and effluent quality, (5) soil moisture conditions, (6) water quality in soil pore, and (7) quality of groundwater.

Selection of tree species: The knowledge of the climate and soil conditions, wastewater quality, and common local pests and diseases is essential for selection of tree species. The availability of a suitable market for selling the tree harvest should also be considered.

Design—initial stand spacing: Initial stand spacing is determined by a combination of factors like wood product desired, irrigation system, and weed control methods. The close spacing for fuel production, moderate spacing for paper production, and wider spacing for a solid wood production is needed to be maintained for getting the desired output.

Site preparation: Site preparation often improves tree survival, establishment, and growth by improving the soil properties and minimizing the vegetation competition. Most important treatments may include removal of unwanted vegetation, slash disposal, leveling, bedding, subsoiling, windrowing, drainage, and use of herbicides.

Planting and maintenance: The saplings of tree species are planted at the predetermined spacing and required quantity of organic matter and fertilizer is added for better growth of the trees.

Management: The various management considerations such as protection from the animals, insects, diseases, and stand treatments needed to be implemented to produce the desired product.

8.4.7.4 Constraint and Challenge in Wastewater Reuse

Despite the important progress and development in wastewater recycling and re-use, the total volume of wastewater produced is quite high compared to its use in the agriculture and forestry sector. At present time, very less development has been made in reusing the wastewater. Therefore, several issues must be taken into consideration and following action plans should be devised, in particular (Moussaoui et al. 2019; NAAS 2022):

- Clear definition of poor-quality water;
- Identification of company and private organization for treatment of wastewater;
- Knowledge of technical and administrative procedure to ensure addressal of the grievances of users, residents and consumers of crops;
- Establishment of criteria and guidelines for project formation, establishment and implementation, evaluation and follow-up of installations;
- Costs involved in the additional treatment requirement are also needed to be taken into consideration;
- Availability of finance for the requirement in developing infrastructure needed for reuse;
- Technical training of wastewater stakeholders including the project managers, employees, and users;
- The direct involvement of actors and users at all levels;
- Integrated management of treated urban wastewater reuse in order to protect environment and public health;
- Guidelines may be prepared for development of landscapes, roadside plantations, kitchen gardens, parks, and tree-based agroforestry systems in urban and peri-urban areas using wastewater generated in cities.

8.5 Conclusions

The use of wastewater in irrigating forest plantations and agroforestry would create opportunities in the form of waste disposal to production. Overall, huge scope exists for innovation in wastewater recycling in terms of its use in irrigating trees, which is an essential tool to reduce the pollution of soil and water resources and mitigating the adverse effect of climate change. Tree plantation can also provide large number of ecological and environmental benefits in addition to recycling and treating wastewater. Appropriate policy, guidelines, and action plans are needed to be developed for achieving the greater benefits from the tree plantations irrigated with the poor-quality water.

References

Adolf VI, Jacobsen SE, Shabala S (2013) Salt tolerance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Environ Exp Bot 92:43–54

Ahmad R, Ismail S (1993) Studies on selection of salt tolerant plants for food, fodder and fuel from world flora. In: Lieth H, Al Masoom AA (eds) Towards the rational use of high salinity tolerant plants: agriculture and forestry under marginal soil water conditions, tasks for vegetation science 28. Kluwer Academic, Dordrecht, pp 295–304

Ahmad R, Khan D, Ismail S (1985) Growth of *Azadirachta indica* and *Melia azedarach* in coastal sand using highly saline water for irrigation. Pak J Bot 17(2):229–233

Ahmad R, Ismail S, Khan D (1987) Saline agriculture at coastal sandy belt. Final research report of coordinated research program on saline agriculture. Karachi University, Karachi, p 183

Allan GL, Fielder SD, Fitzsimmons, Raizada S (2009) Inland saline aquaculture. New technologies in aquaculture: improving production efficiency. Qual Environ Manage 2009:1119–1147

Bala N, Singh G, Bohra NK, Limba NK, Baloch SR (2014) Biodrainage for restoration of canal command waterlogged area in Indian desert. Indian Forester 140(5):462–467

Banyal R, Kumar R, Kumar M, Yadav RK, Dagar JC (2017) Agroforestry for rehabilitation and sustenance of saline ecologies. In: Dagar J, Tewari V (eds) Agroforestry. Springer, Singapore. https://doi.org/10.1007/978-981-10-7650-3_16

Bhardwaj AK, Mishra VK, Arora S, Srivastava S, Singh YP, Sharma DK (2019) Soil salinity and land use-land cover interactions with soil carbon in a salt-affected irrigation canal command of Indo Gangetic plain. Catena 180:391–400

Biswas A, Biswas A (2014) Comprehensive approaches in rehabilitating salt affected soils: a review of Indian perspective. Open Trans Geosci 1:13–24

Chaturvedi AN (1985) Fuelwood farming in degraded lands in the Gangetic plains. UP Forest Bulletin 50. Government of Uttar Pradesh, Lucknow

Dagar JC (2003) Biodiversity of Indian saline habitats and management & utilization of high Salinity tolerant plants with industrial application for rehabilitation of saline areas. In: Alsharhan AS, Wood WW, Goudie AS, Fowler A, Abdellatif EM (eds) Desertification in the third millennium. Swets & Zeitlinger, Lisse, pp 151–172

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh A, Arunachalam A (eds) Agroforestry systems in India: livelihood security & environmental services, vol 10. Springer, New Delhi, pp 273–332

Dagar JC (2018) Utilization of degraded saline habitats and poor-quality waters for livelihood security. Scho J Food Nutr 1(3):115

Dagar JC, Minhas PS (2016a) Agroforestry to rehabilitate the Indian coastal saline areas. In: Dagar JC, Minhas PS (eds) Agroforestry for the management of waterlogged saline soils and poor-quality waters, vol 13. Springer, Cham, pp 121–143

Dagar JC, Minhas PS (2016b) Saline irrigation for productive agroforestry systems. In: Dagar JC, Minhas PS (eds) Agroforestry for the management of waterlogged saline soils and poor-quality waters, vol 13. Springer, Cham, pp 145–161

Dagar JC, Singh G, Singh NT (2001) Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali-sodic soils in India. Arid Land Res Manag 15:115–133. https://doi.org/10.1080/15324980151062742

Dagar JC, Kumar Y, Tomar OS (2005) Performance of ornamental and medicinal periwinkle under saline environment. Indian J Hortic 62(2):175–180

Dagar JC, Tomar OS, Kumar Y, Yadav RK, Tyagi NK (2006) Performance of some under-explored plants under different treatments of saline irrigation in semi-arid climate of north-west India. Land Degrad Dev 17:285–299

Dagar JC, Tomar OS, Minhas PS, Singh G, Ram J (2008) Dryland biosaline agriculture-Hisar experience. Karnal, CSSRI, p 28

Dagar JC, Yadav RK, Ahamad S (2012) *Euphorbia antisyphilitica*: a potential petro-crop for degraded calcareous soils and saline water irrigation in dry regions of India. J Soil Salinity Water Qual 4(2):86–91

Dagar JC, Tomar OS, Minhas PS, Mukesh K (2013) Lemongrass (*Cymbopogon flexuosus*) productivity as affected by salinity of irrigation water, planting method and fertilizer doses on degraded calcareous soil in a semi-arid region of northwest India. Indian J Agric Sci 83(7): 734–738

Dagar JC, Lal K, Ram J, Kumar M, Chaudhary SK, Yadav RK, Ahmad S, Singh G, Kaur A (2016a) Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. Agric Ecosyst Environ 233:33–42

Dagar JC, Yadav RK, Tomar OS, Minhas PS, Gajender Y, Lal K (2016b) Fruit-based agroforestry systems for saline water irrigated semi-arid hyperthermic camborthids soils of north-west India. Agrofor Syst 90(6):1123–1132

Dagar JC, Yadav RK, Gajender (2019) Castor productivity and oil quality under nitrogen and phosphorus levels and saline irrigation in calcareous ustipsamments of North-west India. J Soil Salinity Water Qual 11(2):202–209

Dagar JC, Gangaiah B, Gupta SR (2020a) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, pp 367–424

Dagar JC, Yadav G, Yadav RK (2020b) Medicinal chamomile (*Matricaria recutita* Linn.): a commercial crop for salt-affected conditions in semiarid regions of India. J Soil Salinity Water Qual 12(1):34–44

Dagar JC, Gupta SR, Sileshi GW (2023) Urban and peri-urban agroforestry to sustain livelihood and food security in the face of global environmental change and epidemic threats. In: Dagar JC, Gupta SR, Sileshi GW (eds) Agroforestry for sustainable intensification of agriculture in Asia and Africa. Springer, Cham

Drechsel P, Hanjra MA (2018) Wastewater for greening the desert - Business Models 17. In: Miriam O, Pay D (eds) Resource recovery from waste: business models for energy, nutrient and water reuse in low- and middle-income countries. Routledge, Oxon, pp 595–603

Eaton FM (1950) Significance of carbonates in irrigation waters. Soil Sci 69:123–133

FAO (2008) Land and plant nutrition management service. Food and Agriculture Organization of the United Nations, Geneva

Gentili R, Ambrosini R, Montagnani C, Caronni S, Citterio S (2018) Effect of soil pH on the growth, reproductive investment and pollen allergenicity of *Ambrosia artemisiifolia* L. Front Plant Sci 9:1335

Glenn EP, O'Leary JW, Watson MC, Thompsom TL, Kuehl RO (1991) Salicornia-bigelovii Trr – an oilseed halophyte for seawater irrigation. Science 251:1065–1067

Guo LQ, Shi DC, Wang DL (2010) The key physiological response to alkali stress by the alkali resistant halophyte *Puccinellia tenuiflora* is the accumulation of large quantities of organic acids and into the rhyzosphere. J Agron Crop Sci 196:123–135

Heuperman AF, Kapoor AS, Deneke DW (2002) Biodrainage-principles, experiences and applications. Knowledge synthesis report no. 6 International Programme for Technology and Research in Irrigation and Drainage. FAO, Rome, p 79

Hussain A, Gul P (1993) Selection of tree species suitable for saline and waterlogged areas in Pakistan. In: Davidson N, Galloway R (eds) Productive use of saline land. Australian Centre for International Agricultural Research, Canberra, pp 53–55

Ilyas M, Ahmad W, Khan H, Yousaf S, Yasir M, Khan A (2019) Environmental and health impacts of industrial wastewater effluents in Pakistan: a review. Rev Environ Health 34(2):171–186. https://doi.org/10.1515/reveh-2018-0078

Ismail S, Rao NK, Dagar JC (2019) Identification, evaluation and domestication of alternative crops for saline environments. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer, New York, pp 505–536

Jain BL, Goyal RS, Muthana KD (1983) Performance of some tree species in relation to irrigation with saline waters. Ann Arid Zone 22:233–238

Jena SK, Sahoo N, Roy Chowdhury S, Mohanty RK, Kundu DK, Behera MS, Kumar A (2011) Reclamation of coastal waterlogged wasteland through biodrainage. J Indian Coastal Agric Res 29:57–62

Kalaiselvi P, Sugumaran MP, Subramanian A (2019) Efficient utilization of industrial effluents through agroforestry -scope and potential. In: Parthiban A et al (eds) Multifunctional agroforestry (ecosystem services). Jaya Publishing House, New Delhi, pp 444–465

Kamiab F, Talaie A, Javanshah A, Khezri M, Khalighi A (2012) Effect of long-term salinity on growth, chemical composition and mineral elements of pistachio (Pistacia vera cv Badami-Zarand) rootstock seedlings. Ann Biol Res 3(12):5545–5551

Khan SA, Shukla IN (2003) Suitable MPTs for sodic soils of central plain zone of Uttar Pradesh. Indian J Agroforest 5:119–121

Kidd P, Mench M, Álvarez-López V, Bert V, Dimitriou I, Friesl-Hanl W, Herzig R, Janssen JO, Kolbas A, Müller I (2015) Agronomic practices for improving gentle remediation of trace element-contaminated soils. Int J Phytoremediation 17(11):1005–1037. https://doi.org/10.1080/15226514.2014.1003788

Kumar R, Banyal R, Singh A, Yadav RK (2021) Exploring the genetic variation for sodicity tolerance in *Melia dubia* evolved in Indian conditions. Land Degrad Dev 33:41–54

Ladia S, Goswami G, Sarraf S, Harsh S (2015) Textile wastewater – a threat to Jodhpur. *Int J Engin Res Tech* 3(23):1–3

Maaloul A, Michalet S, Saadaoui E, Ghzel N, Bekir J, Romdhane CB, Mars M, Dijoux-Franca MG, Romdhane M (2019) Effect of treated wastewater on growth and secondary metabolites production of two Eucalyptus species. Agric Water Manag 211:1–9. https://doi.org/10.1016/j.agwat.2018.09.027

Marcone MF (2003) Batis maritime (Saltwort/Beachwort): a nutritious, halophytic, seed bearings, perennial shrub for cultivation and recovery of otherwise unproductive agriculture land affected by salinity. Food Res Int 36:123–130

Minhas PS (1996) Saline water management for irrigation in India. Agric Water Manag 30:1–24

Minhas PS, Dagar JC (2016) Synthesis and way forward: agroforestry for waterlogged saline soils and poor-quality waters. In: Dagar JC, Minhas PS (eds) Agroforestry for the management of waterlogged saline soils and poor-quality waters, vol 13. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2659-8_12

Minhas PS, Gupta RK (1992) Quality of irrigation water–Assessment and management. ICAR, New Delhi

Minhas PS, Yadav RK, Lal K, Chaturvedi RK (2015) Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus *(Eucalyptus tereticornis* Sm.) planted at variable stocking density. Agric Water Manag 152:151–160

Minhas PS, Yadav RK, Aradhana B (2020) Perspectives on reviving waterlogged and saline soils through plantation forestry. Agric Water Manag 2020:106063. https://doi.org/10.1016/j.agwat.2020.106063

Monteverdi MC, Da-Canal S, Del-Lungo A, Masi S, Larbi H, De-Angelis P (2014) Re-use of wastewater for a sustainable forest production and climate change mitigation under arid environments. *Ann Silvicul Res* 38:22–28

Moussaoui TE, Wahbi S, Mandi L, Masi S, Ouazzani N (2019) Reuse study of sustainable wastewater in agroforestry domain of Marrakesh city. J Saudi Soc Agric Sci 18(3):288–293

NAAS (2022) Utilization of wastewaters in urban and peri-urban agriculture. Policy Paper No. 98. National Academy of Agricultural Sciences, New Delhi

Neha YG, Yadav RK, Ashwani A, Rai AK, Meena S, Onishi J, Omori K, Sharma PC (2022) Desalinization effect of simulated cut-soiler based residue filled preferential shallow sub surface drainage improves physiology and yield of rain-fed pearl millet in saline semiarid regions. Land Degrad Dev 33:1758–1770

Paulo JC, Favas JP, Mayank V, Rohan D, Manoj SP (2014) Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora. In: Hernandez-Soriano MC (ed) Environmental risk assessment of soil contamination. IntechOpen, London

Pearlsteina SL, Felger RS, Glenn EP, Harringtond J, Al-Ghanem KA, Nel-sona SG (2012) NyPa (*Distichlis palmeri*): a potential grain crop for saltwater irrigation. J Arid Environ 82:60–70

Qureshi RH, Aslam M, Rafiq M (1993a) Expansion in the use of forage halophytes in Pakistan. In: Davidson N, Galloway R (eds) Productive use of saline land. ACIAR, Canberra, pp 12–16

Qureshi RH, Nawaz S, Mahmood T (1993b) Performance of selected tree species under saline-sodic field conditions in Pakistan. In: Lieth H, Al Masoom AA (eds) Towards the rational use of high salinity tolerant plants (vol 2): agriculture and forestry under marginal soil water conditions, tasks for vegetation science 28. Kluwer Academic, Dordrecht, pp 259–269

Rahneshan Z, Nasibi F, Moghadam AA (2018) Effects of salinity stress on some growth, physiological, biochemical parameters and nutrients in two pistachio (*Pistacia vera* L.) rootstocks. J Plant Interact 13:73–82

Ram J, Dagar JC, Singh G, Lal K, Tanwar VS, Shoeran SS, Kaledhonkar MJ, Dar SR, Kumar M (2008) Biodrainage: eco-friendly technique for combating waterlogging & salinity. TEC Bull 9:24

Ram J, Dagar JC, Lal K, Singh G, Toky OP, Tanwar RS, Dar SR, Mukesh K (2011) Biodrainage to combat water logging, increase farm productivity and sequester carbon in canal command area of north-west India. Curr Sci 100(11):1673–1680

Richards LA (1954) Saline and alkali soils: diagnosis and improvement. In: USDA agriculture research service handbook, p 60

Roy S (2020) Wastewater generation and treatment – present status in India. https://indianinfrastructure.com/2020/02/01/wastewater-generation-and-treatment-present-status-in-india/. Accessed 2021 Jan 15

Roy Chowdhury S, Kumar A, Brahmanand PS, Ghosh S, Mohanty RK, Jena SK, Sahoo N, Panda GC (2011) Application of bio-drainage for reclamation of waterlogged situations in deltaic Orissa. Directorate of Water Management (ICAR), Bhubaneswar, p 32

Sharma DK, Thimmppa K, Chinchmalatpure A, Mandal AK, Yadav RK, Chaudhari SK, Kumar S, Sikka AK (2015) Assessment of production and monetary losses from salt affected soils in India, Technical Bulletin: ICAR-CSSRI/Karnal/2015/05

Singh G (2009) Salinity related desertification and management strategies: Indian experience. Land Degrad Dev 20:367–385

Singh AP (2018) Status report on CETPs, STPs and industrial pollution in Jojari River (Jodhpur to Balotra). Submitted in reference to Hon'ble National Green Tribunal (NGT), New Delhi

Singh G, Bhati M (2005) Growth of *Dalbergia sissoo* in desert regions of western India using municipal effluent and the subsequent changes in soil and plant chemistry. *Bioresour Technol* 96(9):1019–1028

Singh G, Lal K (2014) Bio-drainage for management of waterlogging and soil salinity. https://www.icid.org/report_bmw_n_ss.pdf

Singh G, Lal K (2018) Review and case studies on biodrainage: an alternative drainage system to manage waterlogging and salinity. Irrig Drain 67:51–64. https://doi.org/10.1002/ird.2252

Singh G, Singh NT, Tomar OS (1993) Agroforestry in salt-affected soils. Karnal, CSSRI, p 65

Singh JP, Gangwar B, Pandey DK, Kochewad SA (2011) Integrated farming system model for small farm holders of western plain zone of Uttar Pradesh. Project Directorate for Farming Systems Research, Modipuram, p 58

Singh YP, Singh G, Sharma DK (2014) Bio-amelioration of alkali soils through agroforestry systems in central Indo-Gangetic plains of India. J For Res 25:887–896. https://doi.org/10.1007/s11676-014-0535-1

Singh G, Nagora PR, Haksar P, Chauhan AR (2021) Utilizing treated wastewater in tree plantation in Indian desert: part I - species suitability, plant growth and biomass production. Int J Phytoremediation 25:1–11. https://doi.org/10.1080/15226514.2021.1993784

Singh YP, Mishra VK, Arora S, Dagar JC, Lal K (2022) Restoration of degraded sodic soils through silvopastoral systems in the Indo Gangetic plains. Land Degrad Dev. https://doi.org/10.1002/ldr.4222

Suarez DL (1981) Relationship between pHc and SAR and an alternative method for estimating SAR of soil or drainage water. Soil Sci Soc Am J 45:469–475

Thawale PR, Juwarkar AA, Singh SK (2006) Resource conservation through land treatment of municipal wastewater. Curr Sci 90:704–711

Tomar OS, Minhas PS, Sharma VK, Singh YP, Gupta RK (2003) Performance of 31 tree species and soil conditions in a plantation established with saline irrigation. For Ecol Manag 177:333–346

Tomar OS, Dagar JC, Minhas PS (2010) Evaluation of sowing methods, irrigation schedules, chemical fertilizer doses and varieties *of Plantago ovata* Forsk to rehabilitate degraded calcareous lands irrigated with saline water in dry regions of north western India. Arid Land Res Manag 24:133–151

USDA (2000) United State Department of Agriculture National Agroforestry Center, Nebraska

Vertessy RL, Connell JM, Silberstein A, Heuperman P, Feikema L, Mann M, Komarzynski JC, Stackpolie D (2000) Sustainable hardwood production in shallow watertable areas. AMA House, Kelvin Grove, p 105

Weber DJ, Gul B, Khan MA, Williams T, Wayman P, Warner S (2001) Comparision of vegetable oil from seeds of native halophytic shrubs. In: McArthur ED, Fairbanks DJ (eds) Proceedings of the Shrubland ecosystem genetics and biodiversity. Ogden, Rocky Mountain Research Station, pp 287–290

Weissbein S, Wiesman Z, Ephrath Y, Silberbush M (2008) Vegetative and reproductive response of olive cultivars to moderate saline water irrigation. Hortic Sci 43(2):320–327

Wiesman Z, Itzhak D, Ben-Dom N (2004) Optimization of saline water level for sustainable Bornea olice and oil production in desert conditions. Sci Hortic 100:257–266

Yadav RK, Singh SP, Lal D, Ashok K (2007) Fodder production and soil health with conjunctive use of saline and good quality water on ustipsamments of semi-arid regions. Land Degad Dev 27(8):153–162

Yadav RK, Minhas PS, Lal K, Dagar JC (2016) Agroforestry for the management of waterlogged saline soils and poor quality waters. Adv Agroforestry 13:163–179

Yadav T, Kumar A, Yadav RK, Yadav G, Kumar R, Kushwaha M (2020) Salicylic acid and thiourea mitigate the salinity and drought stress on physiological traits governing yield in pearl millet-wheat. Saudi J Biol Sci 20(8):2010–2019

Yajun B, Xiaojing L, Weiqiang L (2003) Primary analysis of four salt tolerant plants growing in Hai-He plain, China. In: Leith H, Mochtchenko M (eds) Cash crop halophytes: recent studies. Kluwer, London, pp 135–138

Zarrouk M, El Almi H, Ben Youssef N, Sleimi N, Smaoui A, Ben Miled D, Abdelly C (2003) Lipid composition of seed of local halophytes: Cakile maritime, Zygophyllum album and Crithmum maritimum. In: Leith H, Mochtchenko M (eds) Cash crop halophytes: recent studies. Kluwer, London, pp 121–124

Zhang J (2014) Coastal saline soil rehabilitation and utilization based on forestry approaches in China. Springer, Berlin

Zhang X, Takano T, Liu S (2006) Identification of a mitochondrial ATP synthase small subunit gene (RMtATP6) expressed in response to salts and osmotic stresses in rice (*Oryza sativa* L.). J Exp Bot 57:193–200

Chapter 9
Potential of Agroforestry Systems for Food Security, Climate Change Mitigation, Landscape Restoration and Disaster Risk Reduction in Nepal

A. Dhakal and R. K. Rai

Abstract Agroforestry is the oldest form of land use believed to have evolved before sedentary agriculture. In recent years, the importance of integrating trees with crops has been increasingly recognised, not only as a climate change mitigation and adaptation strategy, but also as a viable means of land restoration. There are evidences of agroforestry improving farmers' livelihoods and food security and contributing to land restoration and biodiversity conservation and thereby positively contributing to many of the UN sustainable development goals (SDGs) such as eliminating poverty (#1), clean water and sanitation (#6), climate action (#13) and life on land (#15). Agroforestry, being an integrated and multi-functional land use, holds the potential of becoming an alternative to input-intensive agriculture in Nepal. This chapter presents the dominant forms of agroforestry systems in Nepal and highlights the contribution of these systems to landscape restoration, climate change mitigation and disaster risk reduction. Some agroforestry practices such as timber-based and fishery-based, which are less labour-intensive than input-intensive agriculture, provide opportunity to Nepalese farmers to revive their household economy and thereby address the farmland abandonment issue. The abandoned farmlands, the degraded forests and community forests provide ample avenues for agroforestry promotion in Nepal. However, there are several constraints to its promotion including ambiguous policies, lack of institutional setup, small landholdings and lack of market infrastructure. More research is needed to explore the full potential of agroforestry for livelihood and nutritional security, restoration of degraded landscapes and in climate change adaptation.

Keywords Climate change mitigation and adaption · Fuelwood · Fodder · Livelihoods · Landscape restoration · Disaster risk reduction

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9.1 Introduction

Land degradation and climate change are major challenges of the twenty-first century confronting science and society. The growth of human population in the last 70 years and the need of growing more food to feed the growing population led to more intensive mono-crop production system (MCPS) and high-input agriculture, the ultimate cause of land degradation globally (Al-Wabel et al. 2018). The negative consequence of MCPS is the adverse impact on land, water, biodiversity, forests and overall environment, which are the ecological foundations for sustainable agriculture (Rani et al. 2018; Warren-Thomas et al. 2015). There is clear evidence that the global warming is occurring, and the climate is changing (IPCC 2007, 2021). Intensive agriculture, widespread dependence on fossil fuels, deforestation and carbon emissions from industrial plants contribute to the problem (Maraseni et al. 2020).

Scientists, governments and development and research organisations have attempted to address the problem of land degradation and climate change. In the context of the attempts being ineffective on addressing the issue precisely, now, scientists are emphasising tree growing on agriculture landscapes with field crops, which is commonly known as agroforestry (AF) as a sustainable means of addressing both issues. The practice of MCPS, undoubtedly, has been able to meet the global food demand. However, the negative consequences of the practice led to recognition and appreciation of values of the age-long practice of combining trees with field crops in the same unit of land (Andres et al. 2016; Santos et al. 2019). Several studies confirm that the tree–crop combination has the potential of offering a range of goods and services while contributing to halting land and water degradation, mitigating climate change and biodiversity conservation (Nair 2007; Santos et al. 2019; Dagar et al. 2020).

The term 'Agroforestry' is relatively new to science. However, the practice of integrating trees with agricultural crops is old. The practice is believed to have evolved before sedentary agriculture. There is evidence of home garden evolved during the Mesolithic period (Kumar and Sikka 2014). As primitive as home garden, shifting cultivation, another form of agroforestry, is still widely practised in South American and African countries (Spencer 1966). Also known as 'slash and burn', 'swidden agriculture' and '*Jhum*', this practice is a dominant form of farming system in Southeast Asia and Northeast India (Li et al. 2014; Singh et al. 2014; Behera et al. 2016). Practised in various forms since ancient times, agroforestry is now gradually gaining interest from researchers, landowners and governments. Nair (1993) documented 18 different agroforestry practices under the three broad categories of agroforestry systems, which are in practice globally. As in elsewhere in the world, agroforestry is a form of farming system prevalent since time immemorial in Nepal. Raising trees on marginal lands and around homesteads is a common occurrence in mid-hills region of Nepal. The practice is commonly known as homestead agroforestry which represents a form of subsistence farming system of Nepal (NAF 2005). In recent years, some product-specific agroforestry models are growing at a commercial scale. They include timber-based AF, fishery-based AF (Aqua-silviculture), home garden (horticulture-based), non-timber forest product (NTPF)-based AF and cardamom-based AF (Dhakal et al. 2015; FRTC 2019; Joshi and Joshi 2016). However, they are very localised and have limited geographic coverage (Sharma et al. 2016a).

Nepal has also gone through and witnessed land and water degradation due to adoption of high-input agriculture (Raut et al. 2010; Govaerts et al. 2009; Maraseni et al. 2007). The increased use of agricultural inputs such as fertilisers, pesticides, fuels and farm machinery, directly and indirectly, has accelerated carbon emissions. To address the degradation and emission issue induced by the high-input agriculture in Nepal, a tree-based farming system could be a viable solution.

In this chapter, we describe the dominant forms of agroforestry in Nepal and highlight the potential contribution of agroforestry to the household economy and poverty reduction in the socio-economic context of Nepal. We have briefly examined the role of agroforestry in climate change mitigation and adaptation and disaster risk reduction.

9.2 Geography and Biodiversity Status of Nepal

Geographically, Nepal is a mountainous country, having five distinct physiographic regions—Terai (lowland), *Siwalik/Chure*, Mid-hills, High Mountains and High *Himal*, covering 71% of the total land by the later three (Fig. 9.1). Situated between China and India, it falls within 26°02′ and 30°27′ N latitudes and 80°04′ and 88°22′

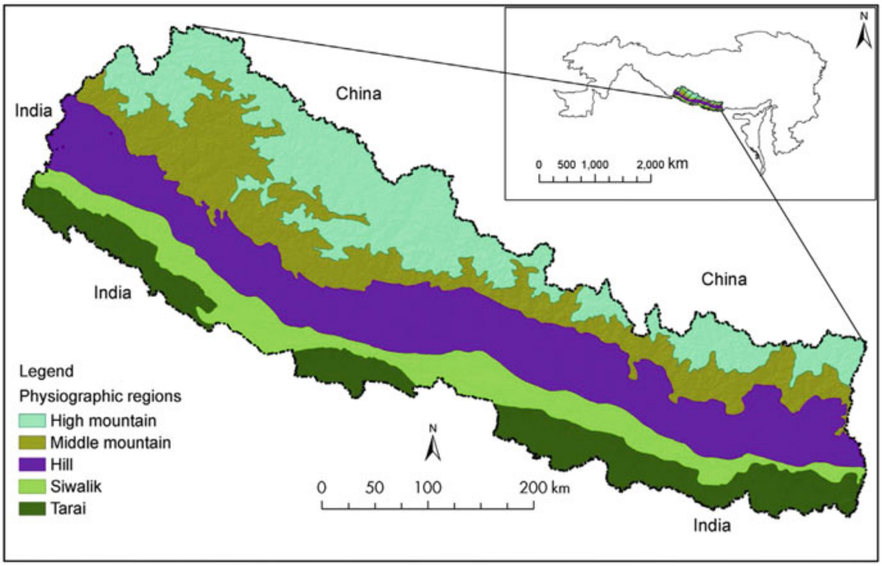

Fig. 9.1 Physiographic zones of Nepal (Uddin et al. 2015)

E longitudes (FRTC 2019). Stretched east to west and 193 km-wide, Nepal covers 0.03% of land area of the world. Ranging from the altitude of 64 m in the south to 8848 m in the north, Nepal is known for its diverse climate varying with its topography. Above 5000 m is the High *Himal*, the northernmost part of the country and it has a very cold and dry climate that hinders tree growth and favours tundra vegetation (MoFSC 2014). The high mountains fall between 4000 and 5000 m representing sub-alpine and alpine climate that favours rangeland and coniferous vegetation and is characterised by steep slopes and deep gorges. The zone between 1000 and 3000 m is called mid-hills which is rich in ecosystem and species diversity and harbours sub-tropical and temperate climate favouring broadleaved and coniferous vegetation. The Siwalik zone falls between 500 and 1000 m and has tropical and sub-tropical climate and dominated by Sal (*Shorea robusta*) forests. Covering 15% of the country's area, the Siwalik zone has a fragile topography and rugged terrain, highly prone to erosion. The region below 500 m is called *Terai* which is rich in fertile soil and therefore termed as the granary of the country. It has tropical climate favouring both evergreen and deciduous broadleaved and riverine vegetation (MoFSC 2014).

Though small, Nepal is known for its diverse ecosystems, flora and fauna. MoFSC (2014) reported that Nepal has 118 different ecosystems and home to 11,971 species of flora and 11,861 species of fauna representing 3% and 1% of the world's known flora and fauna, respectively.

9.3 Dominant Forms of Agroforestry in Nepal

There are three components in an agroforestry system—woody perennials, animals/ pastures and agricultural crops. The necessary condition for a farming system to define as an agroforestry system is the system that must possess woody perennials with one of the other two components or both. Amatya et al. (2018) identified seven agroforestry systems and 35 different variants/sub-categories being practised in Nepal from the low land (*Terai*) to high mountains. The recent study by FRTC (2019) classified agroforestry in 12 different systems, considering horticultural tree species as a separate system component and documented 41 different practices in Nepal under these 12 systems. In the above two studies from Nepal, the researchers used the main product/output as a basis for agroforestry sub-categorisation. These two studies, however, have documented all the agroforestry practices found in Nepal irrespective of their dominance, prevalence, extensiveness and socio-economic significance. Conversely, we document only the dominant agroforestry practices of Nepal, having local and global significance. Home garden and homestead agroforestry represent the traditional form, while the rest are improved agroforestry types (Table 9.1).

Both the traditional and improved agroforestry have been in practice at various scales—subsistence to commercial—depending on farmers' needs, experience and market infrastructure. In Nepal, homestead agroforestry and home garden (Table 9.1) are two traditional, dominant forms of agroforestry which Nepalese

Table 9.1 Dominant agroforestry practices of Nepal

SN	Types	Main output	Major woody perennials	System defined	Scale	Geographic coverage	Sources
1	Fodder-based agroforestry	**Primary:** Fodder and grass (goat /cattle) **Secondary:** Firewood	**1. Fodder species** *Ficus semicordata, Litsea monopetala, Artocarpus lakoocha, Leucaena latisiliqua, Ficus glaberrima, Morus alba, Grewia optiva, Melia azedarach, Ficus roxburghii, Ficus hipsida, Flemingia congesta, Ficus glaberrima, Ficus racemosa, Saurauia nepaulensis* and *Ficus lacor* (**Mid-hills**) **&** *Ficus semicordata, Morus alba, Litsea monopetala, Artocarpus lakoocha, Leucaena latisiliqua, Melia azedarach, Bauhinia variegata, Premna latifolia, Garuga pinnata, and Gmelina arborea* (**Terai**) **2. Forage species** *Stylosanthes guianensis, Melinis minutiflora, Vicia species, Trifolium repens, Setaria anceps*, and *Pennisetum purpureum*	Agrosilvopastoral **&** Silvopastoral	Subsistence **&** Commercial	Mid-hills **&** *Terai*	Amatya et al. (2018), FRTC (2019), Pandit et al. (2014), NAF (2005), Dhakal et al. (2012); Neupane and Thapa (2001)

(continued)

Table 9.1 (continued)

SN	Types	Main output	Major woody perennials	System defined	Scale	Geographic coverage	Sources
			(**Mid-hills**) **&** *Lolium perenne, Zea mays* subspp *parviglumis, Vicia* spp, *Lupinus angustifolius, Arachis glabrata, Avena sativa, Trifolium repens,* and *Desmodium spp.* (**Terai**)				
2	Timber-based agroforestry	**Primary:** Timber and poles **Secondary:** Firewood and fodder	*Alnus nepalensis, Paulownia tomentosa, Michelia champaca, Rhododendron arboreum,* and *Taxus wallichiana* (**Mid-hills**) **&** *Eucalyptus camaldulensis, Tectona grandis, Melia azedarach, Gmelina arborea, Anthocephalus chinensis, Dalbergia sissoo, Shorea borneensis Albizia procera, Bombax ceiba, Populus sp.* and *Paulownia tomentosa* (**Terai**)	Agrisilvicultural, Wood-lot/agroforest, Silvopastoral **&** Agrosilvopastoral	Commercial	Central and eastern Terai **&** Mid-hills	Amatya et al. (2018), FRTC (2019), NAF (2005), Dhakal et al. (2012), Dhakal and Rai (2020)
3	Coffee-based agroforestry	**Primary:** Coffee **Secondary:**	**Coffee species:** *Coffea arabica* and *Coffea robusta* **Tree species:**	Agrisilvicultural	Commercial	Central **&** Western Mid-hills	Sharma et al. (2016a), Tuladhar and Khanal (2018), Karki et al. (2018),

		Timber and firewood	*Elaeocarpus ganitrus, Choerospondias axillaris, Michelia champaca, Toona ciliata, Melia azedarach* and *Castanopsis indica*				Acharya and Dhakal (2014), Pandit et al. (2015)
4	Cardamom-based agroforestry	**Primary:** Cardamom **Secondary:** Timber, fruit, NTFPs and firewood	*Elaeocarpus ganitrus, Alnus nepalensis, Schima wallichi, Castanopsis indica,* and *Cinnamomum tamala.*	Agrisilvicultural	Commercial	Eastern Mid-hills **&** Sporadic in central and western mid-hills	Sharma et al. (2007), Kalauni and Joshi (2019), Pandit et al. (2018)
5	NTFPs-based agroforestry	**Primary:** NTFPs and MAPs (tea, broom, cinna-mon, *chiraito* etc.) **Secondary:** Timber, and firewood	*Camelia sinensis* (tea), *Thysanolaena latifolia* (broom grass), *Alnus nepalensis, Paulownia tomentosa, Michelia champaca, Rhododendron arboretum, Zanthoxylum armatum, Cinnamomum tamala, Taxus wallichiana, Albizia procera, Dalbergia sissoo, Eucalyptus camaldulensis* and *Mangifera indica*	Agrisilvicultural, Hortisilvicultural **&** Agrosilviherticultural	Intermediate **&** Commercial	Mid-hills **&** *Terai*	FRTC (2019), Amatya et al. (2018)
6	Horticulture-based agroforestry	**Primary:** Fruits **Secondary:** Timber, fodder, NTFPs and firewood	*Malus domestica* (apple), *Salix* species, *Populus* spe-cies, *Pinus wallichiana* and Juniperus species (**High mountains)** Citrus spp., *Juglans regia* (walnut), *Musa sapientum*	Hortisilvicultural Agrosilvihorticultural **&** Hortiagricultural	Intermediate **&** Commercial	High moun-tains Mid-hills **&** *Terai*	FRTC (2019), Amatya et al. (2018), Dhakal et al. (2015)

(continued)

Table 9.1 (continued)

SN	Types	Main output	Major woody perennials	System defined	Scale	Geographic coverage	Sources
			(banana), *Pyrus communis* (pear), *Choerospondias axilaris* (hog plum), Litsea monopetala, *Myrica esculenta, Elaeocarpus ganitrusa, Michelia champaca, Ficus semicordata, Artocarpus lakoocha, Leucaena latisiliqua,* and *Ficus lacor* (**Mid-hills**) **&** *Mangifera indica* (mango), *Litchi chinensis* (litchi), *Artocarpus heterophyllus* (jackfruit), *Psidium guajava* (guava), *Areca catechu* (betel nut), *Musa sapientum* (banana), *Eucalyptus camaldulensis, Tectona grandis, Melia azedarach, Litsea monopetala, Shorea borneensis, Ficus semicordata, Artocarpus lakoocha,* and *Leucaena latisiliqua* (**Terai**)				

7	Coconut-based agroforestry	**Primary:** Coconut fruit and betel nut **Secondary:** Timber, fodder, coffee and firewood	*Cocos nucifera* (coconut), *Areca catechu* (betel *nut),* citrus spp., *Musa sapientum, Psidium guajava, Dalbergia sissoo, Eucalyptus camaldulensis, Melia azedarach*	Agrosilviherticultural Hertiagricultural **&** Agrosilvicultural	Intermediate **&** Commercial	Eastern *Terai*	Sherchan et al. (2021), Amatya et al. (2018), Ghimire and Dhungana (2021), Acharya et al. (2021)
8	Apiculture-based agroforestry	**Primary:** Honey **Secondary:** Fruits, timber, fodder, and firewood	*Citrus spp., Pyrus pashia, Pyrus communis, Diploknema butyracea, Schima wallichii, Castanopisus indica, Prunus cerasoides* and *Rhododendron arboreum* (**Mid-hills**) *Bombax ceiba, Callistemon viminalis, Prunus persica, Litchi chinensis, Psidium guajava,* and *Moringa oleifera* (**Terai**)	Agrisilvicultural	Commercial	Mid-hills **&** *Terai*	Amatya et al. (2018), Adhikari and Ranabhat (2011)
9 & 10	Homestead agroforestry/ home garden	Subsistence needs of households (timber, fodder, firewood, fruits etc.)	*Ficus semicordata, Litsea monopetala, Artocarpus lakoocha, Leucaena latisiliqua, Ficus glaberrima, Morus alba, Grewia optiva, Melia azadarach, Ficus roxburghii, Ficus hipsida, Flemingia congesta, Ficus glaberrima, Ficus recemosa, Saurauia nepaulensis, Ficus lacor,*	Agrisilvicultural Hortisilvicultural Agrosilvihorticultural Hortiagricultural **&** Agrosilvicultural	Subsistence	Mid-hills **&** *Terai*	Amatya et al. (2018), FRTC (2019), NAF (2005), Dhakal et al. (2012), Dhakal and Rai (2020), Neupane and Thapa (2001)

(continued)

Table 9.1 (continued)

SN	Types	Main output	Major woody perennials	System defined	Scale	Geographic coverage	Sources
			Alnus nepalensis, Paulownia tomentosa, Michelia champaca, Rhododendron arboretum, Schima wallichi, Castonopsis indica, Choerospondis axillaris, Taxus wallichiana and *Citrus* spp. (**Mid-hills**) **&** *Ficus semicordata, Morus alba, Litsea monopetala, Artocarpus lakoocha, Leucaena latisiliqua, Melia azedarach, Bauhinia variegata, Premna latifolia, Garuga pinnata*, and *Gmelia arborea, Eucalyptus camaldulensis, Tectona grandis, Melia azedarach, Gmelina arborea, Anthocephalus chinensis, Dalbergia sissoo, Shorea borneensis Albizia procera, Bombax ceiba, Populus sp., Paulownia tomentosa, Mangifera indica*, *Litchi chinensis*, *Artocarpus heterophyllus*, and *Psidium guajava* (**Terai**)				

11	Fishery-based agroforestry	**Primary:** Fish **Secondary:** Timber, fodder, grass and firewood	*Eucalyptus camaldulensis, Melia azedarach, Tectona grandis, Dalbergia sissoo, Mangifera indica, Paulownia tomentosa,* and *Shorea borneensis*	Aqua-silviculture **&** Agrosilvifishery	Commercial	Eastern and central *Terai*	FRTC (2019), NAF (2005)
12	Sericulture-based agroforestry	**Primary:** Fodder for silk-worm and silk cocoon **Secondary:** Firewood	*Morus alba* and *Ricinus communis*	Agrisilvicultural **&** Agrosilvopastoral	Commercial	Central and western Mid-hills	Amatya et al. (2018)

Fig. 9.2 (**a**) Homestead agroforestry (farm boundary-*above* and marginal land-*below*) in western *Terai* (*Dang* district). (**b**) Fodder (*Leucaena latisiliqua*)-based agroforestry in western mid-hills (*Tanahun* district)

farmers have practised since time immemorial (Amatya et al. 2018; Atreya et al. 2021). These two practices support smallholder farmers to meet their subsistence needs of firewood, fodder, fruits, vegetables and timber and are not market-driven (NAF 2005). Homestead agroforestry utilises marginal areas which would, otherwise, remain uncultivated, and the spare areas around the household. In a broader term, home garden falls under the homestead agroforestry category (Fig. 9.2a).

Fodder-based agroforestry (Fig. 9.2b) is one of the ten practices getting popular following the introduction of improved breeds of goat, buffalo and cattle in Nepal. Goat farming is flourishing more rapidly in recent years than cattle and buffalo farming because of less labour and land it needs and return to investment being higher (Panth et al. 2021).

Timber-based agroforestry is popular in the *Terai* region of Nepal, specifically central and eastern *Terai* and sporadic in the mid-hills. In the *Terai,* farmers prefer to grow *Eucalyptus camaldulensis, Tectona grandis, Dalbergia sissoo, Populus* spp., *Gmelina arborea, Melia azedarach, Shorea borneensis Albizia procera, Bombax ceiba, Paulownia tomentosa* and *Anthocephalus chinensis* as agroforests/woodlots on their farms with agricultural crops (Table 9.1, Fig. 9.3a). In the mid-hills, most preferred species are *Alnus nepalensis, P. tomentosa, Michelia champaca, Rhododendron arboreum* and *Taxus wallichiana*. Small-scale farmers are not interested in this agroforestry because they are unable to afford the initial production loss resulting from land sparing between trees and agricultural crops (Dhakal and Rai 2020).

Cardamom-based agroforestry is a promising land use in the eastern mid-hills of Nepal. Though extensive in the eastern mid-hills, it is sporadic in central mid-hills (Table 9.1, Fig. 9.3b). Farmers prefer to grow large cardamom (*Amomum subulatum*) under the shades of *Elaeocarpus ganitrus*, *Castanopsis indica, Cinnamomum tamala, Alnus nepalensis* and *Schima wallichi* that help fulfil the subsistence needs of fuelwood, fodder and timber of cardamom growers.

Fig. 9.3 (**a**) Timber/poles (*Eucalyptus camaldulensis*)-based agroforestry in central *Terai* (*Dhanusha* district). (**b**) Cardamom-based agroforestry in eastern mid-hills (*Ilam* district)

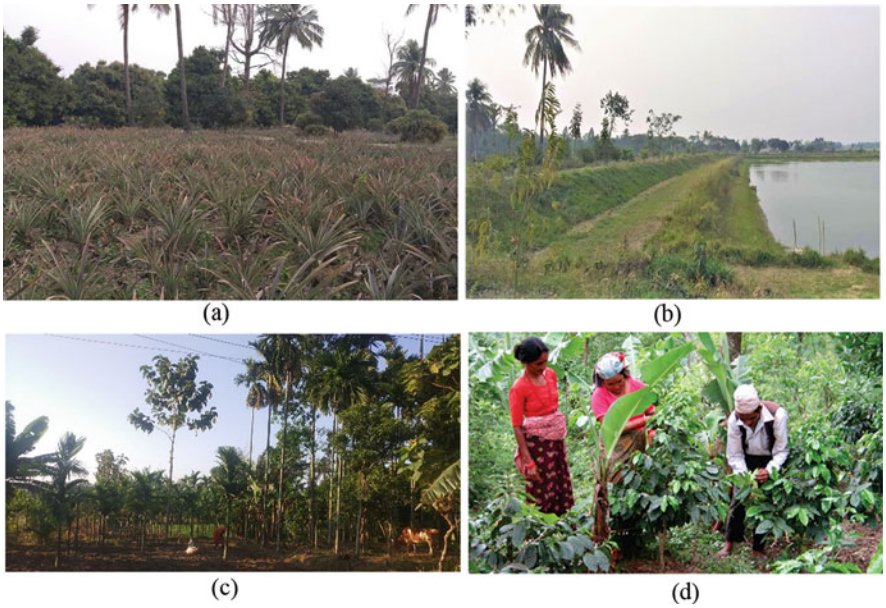

Fig. 9.4 (**a**) Horticulture (mango + pineapple)-based agroforestry in eastern *Terai* (*Morang* district). (**b**) Fishery-based agroforestry (Aqua-silviculture) in central *Terai* (*Dhanusha* district). (**c**) Nut-based agroforestry in eastern *Terai* (*Jhapa* district). (**d**) Coffee-based agroforestry in central mid-hills-*Kavrepalnchowk* district. (Source: http://www.coffeenepal.org.np)

Horticulture-based agroforestry is not localised unlike cardamom-based agroforestry. Though the farmers with enough land are inclined, the practice has been found to have adopted in all regions—high mountains, mid-hills and *Terai* (*Terai* + Siwalik). The dominant horticultural tree species of this agroforestry are apple, citrus spp. and mango in the three regions, respectively (Table 9.1). Depending on needs, farmers choose other horticultural crops and AF tree species to associate with the dominant ones (Fig. 9.4a). Fishery-based agroforestry is another improved agroforestry dominant in eastern and central Terai of Nepal (Table 9.1). Both perennial (tree crops) and annual crops (grass species) are grown on the dike of fishponds (Fig. 9.4b). The purpose of these crops is to meet the farmers' subsistence needs of fruits, fodder and fuelwood, and to some extent provide grass feeds to the fish. Coconut-based agroforestry and coffee-based agroforestry are equally popular farm enterprises in Nepal (Table 9.1, Fig. 9.4c, d).

9.4 Role of Agroforestry in Household Economy

Agroforestry has been a source of livelihoods for millions of people globally. A survey conducted in Dhading district of Nepal revealed that 25% of the respondents were self-sufficient for fodder and firewood from trees grown in and around their homesteads, while 75% of the respondents still used natural forests to fulfil 25% of their annual fodder and firewood needs (NAF 2005).

Out of 12 practices (Table 9.1), 10 practices are product-based, commercial and market-driven (FRTC 2019). These practices are comparatively recent, more localised and less extensive than homestead agroforestry, and most of them are adopted only by affluent people who possess enough land (Dhakal et al. 2015; Dhakal and Rai 2020). There are numerous studies from the mid-hills region of Nepal that confirmed that fodder-based agroforestry generates more income and diversifies farm products than conventional agriculture. Pandit et al. (2014) found the production of milk and meat to have increased significantly in households that raise on-farm fodder trees than those without trees. Neupane and Thapa (2001) revealed that the fodder-based agroforestry almost doubled the farm production in unirrigated (rainfed) land compared to conventional farming system. Cedamon et al. (2019) found that the fodder trees increased the income of project farmers from livestock keeping by 100%. Further, a study from Dhading district revealed an increase in fodder trees on farmlands diversified and increased farm income and greatly saved women's time for fuelwood and fodder collection (Regmi 2003).

Even though timber-based agroforestry has the potential of generating higher NPV and return-to-labour than conventional agriculture, land has been the major constraint to its wider adoptability in the region (Dhakal and Rai 2020; Dhakal 2013). Cedamon et al. (2019) in their study from two mid-hills districts (Kavre and Lamjung) confirmed that the food security index (FSI) of the project farmers improved by two- to threefold due to timber (*A. nepalensis*)-based agroforestry. In future, the scope of this agroforestry practice is expected to be widened, given the labour scarcity resulting from out-migration of youths for jobs (Dahal et al. 2020).

In a study from Bhojpur district, Kalauni and Joshi (2019) revealed that cardamom alone covered more than 45% of the annual household income. KC and Upreti (2017) estimated that about 67,000 households engaged in cardamom-based agroforestry. The practice appeared to be more profitable as it generates B/C ratio of 13.2 which is 7 times higher than that of rainfed agriculture (1.9) (Sharma et al. 2007). Pandit et al. (2018) studied five product-specific agroforestry practices—

cardamom-based, fodder-based, banana-based, chilli-based and ginger-based—and found cardamom-based agroforestry generating the highest profit (USD 2176.4 ha^{-1} $year^{-1}$) followed by horticulture (banana)-based agroforestry (USD 2051.8 ha^{-1} $year^{-1}$). Since this high-value AF crop requires no fertile farmland and it can grow well in marginal and degraded slopes, cardamom has become a sustainable source of household income, thereby supporting smallholder farmers in poverty reduction (KC et al. 2016; Matthys et al. 2021).

9.5 Role of Agroforestry in Climate Change Mitigation and Adaptation

It is estimated that 10–12% of total global GHG emissions comes from agriculture; the figure will go up to 13–18% if indirect sources are included (Maraseni et al. 2020). Compared to two giant neighbouring countries, China and India, Nepal's emission is insignificant, only 0.027% of total global emissions (MoPE 2016). Agriculture is the major source of GHG emission contributing more than 50% of total Nepal's emissions. There have been attempts from the government and non-governmental organisations to reduce agricultural emission by engaging Nepalese farmers in various farming activities that include conservation farming, biochar technology, minimum tillage/zero tillage, organic farming and tree raising on farmlands (Pandit et al. 2020; Thapa et al. 2018; Dhakal 2013). Among these climate-smart activities, agroforestry clearly stands out for its climate change mitigation and adaptation potential. Agroforestry contributes to mitigation in three ways: (1) It stores carbon as tree biomass- above- and belowground; (2) It reduces pressure on natural forest, thus supporting carbon storage in the forest; and (3) It adds organic matter to soil and helps to form soil organic carbon (SOC) after decomposition (Kim et al. 2016; Dhakal 2013). However, the sequestration potential largely depends on the types and age of agroforestry, climate, previous land use, type and density of tree species and tree management (Table 9.2). Feliciano et al. (2018) found that the Silvopastoral system sequesters more soil carbon, while more above-ground C sequestration occurs in improved fallows. The total C (both biomass and soil) was found greater in agroforestry systems in the tropics than those in other climates (Feliciano et al. 2018).

Not only tree biomass carbon, more SOC can be expected in agroforestry-based farming system than in conventional agriculture because of more organic matter likely to add into the soil. In a study from the eastern mid-hills of Nepal, Sharma et al. (2007) reported that the SOC was 3.5 times more in cardamom-based agroforestry than in rainfed agriculture. A fodder-based agroforestry has the potential of capturing more SOC than a tree-less farming system (Bajracharya et al. 2015; Pandit et al. 2013). Depending on the types of agroforestry, the SOC potential varies (Table 9.2). In a study by Magar et al. (2020) from the central Terai of Nepal, they found that a Silvopastoral system had a higher amount of SOC than agroforest/

Table 9.2 Carbon uptake and water retention by different agroforestry practices

Land-use types	Biomass carbon stock (Mg ha^{-1})	Soil organic carbon (Mg ha^{-1})	Soil loss (kg ha^{-1})	Water retention (%)	Sources
Fodder-based AF	48.7	24.41	–	–	Neupane and Thapa (2001), Schwab et al. (2015), Pandey et al. (2019), Sharma et al. (2007), Shrestha et al. (2004), Bhatt (2013), Pandit et al. (2013), Dahal et al. (2020)
Rainfed agriculture	–	12–38	477–1260	83–90.5	
Cardamom-based AF	15.54–128.3	65.27–121.00	30–450	86–97.8	
Horticulture-based AF	–	–	145	95.2	
Coffee-based AF	0.33–0.46	–	–	–	
Forests	–	36.31	74	94.4	
Homestead AF	20.89	–	–	–	
Timber-based AF	–	30.25	–	–	
Home garden	–	24.94	–	–	
Bare land	–	–	3460	26	

woodlot and home garden. More SOC was reported in fodder-based agroforestry than in traditional homestead agroforestry in *Rasuwa* district in central high-hills (Bhatt 2013).

The impact of climate change on agriculture has become obvious in recent years. Climate change is expected to reduce global crop yields (Ray et al. 2019). Like elsewhere, Nepalese farmers have experienced decreased farm production due to extreme weather events (EWEs) such as cold spells, floods and heat waves (Budhathoki et al. 2020). The impact of EWEs is not confined to crop yields only, its long-term consequences are damage to water sources, ecosystems, biodiversity and human health and well-being. In developing countries like Nepal where farmers are unable to afford advanced technologies to cope with EWEs, there is a need of locally available and affordable adaptation strategies to reduce the economic, social and ecological risks due to such EWEs. Out of many locally affordable adaptation strategies such as changes in farm management and landscape, seeking off-farm employment, emergency management planning, purchasing crop insurance and the raising of awareness (Biggs et al. 2013; Adhikari et al. 2018; Budhathoki et al. 2020), the change in agriculture landscape by introducing trees on farm could address the climate risks more holistically. Agroforestry can be an effective coping strategy by providing farmers with timber, fuelwood, fruits and other AF products to sell in the market when agricultural crops are lost due to floods and drought (Quandt 2020).

For many reasons, agroforestry can be a better land-use option to increase the adaptive capacity of farmers and make them less vulnerable to climate variability and change. First, the deep root system of trees helps go deep into the soil for water and nutrients (Soni et al. 2017) which will help agricultural crops during droughts. Second, agroforestry increases soil porosity and soil cover and decreases runoff, which promotes water infiltration and retention in the soil, contributing to water stress reduction during low rainfall seasons (Apuri et al. 2018). Third, tree-based farming systems are more diversified and therefore, less risky than other agricultural land uses because of a variety of products, which reduces the likelihood of complete crop failure (Kebebew and Urgessa 2011). Fourth, trees possess the capacity to adapt to a wide range of ecological conditions as demonstrated by *Eucalyptus* species, *Acacia nilotica*, *Dalbergia sissoo* and *Terminalia arjuna* in Mwanga district of Tanzania (Charles et al. 2013).

The above studies from Nepal and other countries signify the importance of agroforestry for global emission reduction efforts and as an adaptation strategy. However, due to lack of data about the total land under agroforestry, it is hard to estimate the actual contribution to climate change mitigation. If the abandoned land, which is now mostly covered with invasive plants (Jaquet et al. 2015), is to be brought under agroforestry, a huge amount of C can be stored, both in biomass and soil.

9.6 Role of Agroforestry in Land Restoration

There are a wealth of literature supporting that agroforestry provides numerous environmental benefits. One of them is land restoration. Land restoration means reducing soil erosion, soil fertility improvement, nutrient cycling, and water retention and quality improvement (Nair and Garrity 2012; Sharma et al. 2007; Dagar 2018; Dagar and Singh 2018; Dagar et al. 2020; Shin et al. 2020). The tree component of agroforestry by adding organic matter (OM), which turns into soil nutrients after decomposition, helps to improve soil health and maintain land productivity (Jose 2009).

In a study conducted in a mid-hills district (Nuwakot) by Schwab et al. (2015), it was found that a mature agroforestry (>15 years) can store more organic matter (OM), nitrogen (N) and phosphorus (P) than conventional agriculture. Except for N, Pandey et al. (2019) found the amounts of P and K to be higher in an agroforestry system with neutral pH than in agricultural soil with slightly alkaline pH. Sharma et al. (2007) compared the role of four land-use systems in soil and water conservation and found that the soil loss from cardamom-based agroforestry was significantly lower than the other three land-use systems—forests, horticulture-based agroforestry and rainfed agriculture. In terms of water conservation, the water retention capacity of cardamom-based agroforestry was 86%, which was higher than that of rainfed agriculture (Table 9.2).

There are examples of agroforestry restoring degraded forest land. About 43,993 ha of degraded forest has been reforested with agroforestry (horticulture-based, fodder/forage-based and NTFP-based) under the leasehold forestry programme (Kafley and Pokharel 2017). The degraded forests have improved their quality in terms of vegetation coverage and biodiversity. Ohler (2000) reported that vegetation coverage has changed from 32% to 90% due to agroforestry adoption, followed by grazing control in the forest. The FAO report (2013) mentions that 57% of the leasehold groups perceived an increase in vegetation and reoccurrence of many birds, reptiles and mammals in the forest.

9.7 Role of Agroforestry in Disaster Risk Reduction

Nepal is highly vulnerable to natural disasters such as floods, landslides and drought, given its fragile landscapes and mountain terrain. The unsustainable development works such as haphazard road construction and unsustainable agriculture such as marginal land cultivation has further increased the risk of such disasters in the country (Koirala et al. 2021). Studies suggest that trees can play a crucial role in disaster risk reduction as they can function as buffer to control floods, and as windbreaks and shelterbelts to conserve soil from being eroded by wind and soil moisture during drought (Zhang et al. 2019). A study from Nuwakot district of Nepal confirms that agroforestry contributed to building a resilient rural economy by checking natural disasters and thereby, reversing the environmental degradation (Schick et al. 2018). There is evidence of agroforestry such as hedgerow plantation effectively checking landslides and controlling soil erosion from agricultural lands in the hilly region of Nepal (Shrestha 2002; Tiwari et al. 2008).

Agroforestry can function as a drought-checker. The tree component of the system breaks the wind speed and provides shades, which help retain soil moisture. This is supported by a study from a mid-hills district of Nepal (Paudel et al. 2019). In lowland of Nepal, it is widely assumed that farmers practise agroforestry to avoid the threat of sedimentation to agriculture land because of flooding. Conversely, studies have shown that this is not a major determinant of agroforestry decision in the Terai (Dhakal et al. 2015). Nonetheless, agroforestry is a widely recommended strategy for degraded land and flooded area reclamation in Nepal (Kafle 2006).

9.8 Constraints to Agroforestry Promotion in Nepal

9.8.1 Farmland Size

Land size has not been an issue for traditional forms of agroforestry (homestead and home garden) in Nepal. Farmers use marginal lands and spare areas around dwellings for homestead agroforestry and home garden, thus making no impact on the major crop production. Trees are also grown in terrace risers, farm bunds and along farm borders in a scattered fashion as homestead agroforestry, making sure the presence of trees will not have severe impact on farm production (NAF 2005; Dhakal et al. 2015). Conversely, for improved agroforestry practices that are more commercial, and market-driven, land size has been an issue. Because of the time it takes for AF trees ready for harvest, it is hard for smallholder farmers to shift from a treeless farming to tree-dominant farming system such as timber-based agroforestry. Dhakal and Rai (2020) concluded in their study from *Dhanusha* district in *Terai* that timber-based agroforestry is purely the affair of large-scale farmers who can afford the initial loss in farm production. This conclusion has been supported by many studies. For example, Neupane et al. (2002), Dhakal et al. (2015) and Cedamon et al. (2018) all reported that the farmland size was the most influential factor for deciding agroforestry adoption in both hills and *Terai* of Nepal. Similarly, Bhandari et al. (2021) found that middle-class households are more likely to grow more trees on their farmlands than poor households.

9.8.2 Ambiguous Policy

Unlike agriculture and forestry, agroforestry has not been a government's priority; it is a neglected farming sub-sector in Nepal, having no institutional and policy back up for its promotion. Agroforestry being a hybrid farming practice combining two or more sub-sectors—forestry, agriculture and livestock—is influenced by rules and regulations of these sub-sectors. Lack of independent agroforestry rules and regulations creates problems in the transportation of farm-grown trees and NTFPs (NAFP 2019). For example, all the tree-based products—either farm-grown or harvested from the forest—are treated as forest products and come under the jurisdiction of the department of forests. Farmers are to follow the prevailing forestry rules for their product harvest, sale and distribution. In addition, there is a series of bureaucratic formalities to follow by farmers from the raising of trees to harvesting and post-harvesting (FRTC 2019). The rent-seeking government officials make the bureaucratic formalities further complicated. Unlike tree-based products, there are no such legal formalities for agricultural and livestock products. As a result of such an ambiguous policy in place, agroforestry could not get momentum in the country. Very recently, there has been a policy breakthrough that the Government of Nepal has endorsed a new policy—the National Agroforestry Policy (NAFP)-2019, the impact of which is yet to be realised at the farm level. However, the recently endorsed forest policy, National Forest Policy-2018, has created confusion by dividing the on-farm trees into three categories as agroforestry, family forestry and private forestry, which contradicts with the crux of NAFP-2019. Fundamentally, the latter two are not different from agroforestry.

9.8.3 Lack of Adequate Market Infrastructure

Even though market-driven agroforestry practices are emerging in Nepal, lack of adequate market infrastructure is hampering the expansion of such promising, commercial practices. Farmers are deprived of getting reasonable price for their agroforestry products due to middlemen-controlled market structure, which keeps the price fluctuating (ICIMOD 2019). A study by Shrestha et al. (2018) shows the price of large cardamom in Eastern Nepal to have decreased by 30% in the last 4 years. In a recent study, Acharya et al. (2021) highlighted the need of a mechanism for connecting producers directly with consumers to avoid the middlemen dominance. In their study, they explicitly identified '*limited access to Indian transport infrastructure*', '*lack of accredited laboratories*' and '*lack of warehouses for storage*' as major constraints to promotion of cardamom-based agroforestry in the region.

The timber market in central *Terai* of Nepal is no different, which is also dominated by middlemen, known as contractors who negotiate the price with the timber producers. Dhakal (2013) studied the timber market in Dhanusha district and found that the on-farm *Eucalyptus* trees were traded through middlemen, who determine the price on a per-tree basis, not on a volume basis by considering all the seen and unseen costs associated with the timber trade. They also take advantage of the ambiguous policy about the farm-grown forest products while negotiating the price. A road network is a foundation and therefore, essential for commercialising and creating markets for AF products. This is supported from a study by Dhakal et al. (2012) who found that the households linked with the main highway are more likely to adopt horticulture-based agroforestry than the unliked households. The National Agroforestry Policy-2019 also highlights the lack of a market with attractive prices for agroforestry products as one of the bottlenecks for the expansion of agroforestry in the country.

9.8.4 Lack of Institutional Set Up for Agroforestry Research and Development

Even though agroforestry has the potential of making positive impacts at various spatial scales—increased farm productivity, increased soil fertility, decreased soil erosion and enhanced biodiversity at the local scale, decreased downstream impacts (flood control, low concentration of NPK in water bodies) at the regional scale, and increased biomass carbon and SOC contributing to climate change mitigation at the global scale, it still remains a neglected form of farming system globally and in Nepal. A need of separate institutional set up, unlike forestry, agriculture and livestock, has never been felt for the promotion and expansion of such a promising land use in Nepal. As a result, there has not been systematic efforts for agroforestry research and development in the country (Amatya et al. 2018). This is not to say there has been zero efforts; there are institutions—both government and non-government—involved in agroforestry research and development (Atreya et al. 2021). The efforts made so far, however, appear to be scanty, sporadic and mostly donor-driven, thus failing to make visible impacts. Studies suggest that the donor-driven projects are short lived, and farmers discontinue them after the support ends (Adesina and Chianu 2002). Even the successful models of agroforestry such as fodder-based, sericulture-based and timber-based fail from being upscaled due to lack of institutional support, arising from the ambiguity among the government institutions/entities (agriculture, forest and livestock) about who the responsible body is for the extension and promotion of agroforestry in Nepal (NAF 2005).

9.9 Prospects of Agroforestry Promotion in Nepal

9.9.1 Endorsement of Agroforestry Policy

Nepal has become the second country after India to endorse a separate agroforestry policy. The policy is a positive initiative of the government and is expected to create a favourable environment for agroforestry promotion in the country. The policy has identified agroforestry as a potential land-use system for addressing the issue of agricultural land resulting from labour shortage in recent years in the country (NAFP 2019). To some extent, the policy attempts to address the policy ambiguity about farm-grown tree products. The highlights of the policy are provision of insurance for tree crop damage or loss, and market and physical infrastructure development for commercialising agroforestry. Some other provisions such as tree crops as collateral for bank loans, exemption of interest until the harvesting of the crops and exemption of loan at the time of natural disaster are in favour of farmers interested in agroforestry adoption.

9.9.2 Abandoned Farmland, Degraded Forest Land and Community Forest

The trend of farmland abandonment continues to grow, since the trend of youth going abroad has also increased over the years, creating a huge gap between labour demand and supply (Dahal et al. 2020). It is estimated that 25% of the cultivated land has been left uncultivated (MoALD 2019). The abandoned farmlands are being invaded with unwanted vegetation, which is a sign of land degradation (Jaquet et al. 2015). The recently amended land-use policy-2019 has a provision of no land abandonment. Therefore, farmers are in search of land-use alternatives that require minimum labour inputs and can reverse the land degradation while meeting the legal obligations. Studies suggest that there are less-labour intensive agroforestry practices, and these practices can be an effective land restoration strategy (Dhakal 2013; Dhakal et al. 2015; Schwab et al. 2015; Pandey et al. 2019; Sharma et al. 2007). The land once a limiting factor for agroforestry practice is now available in the form of abandoned land, which is an opportunity for agroforestry promotion in the country. Timber-based agroforestry, NTFP (broom grass)-based agroforestry, fishery-based agroforestry and horticulture-based agroforestry are recommended as low-input (labour) farming practices (Dahal et al. 2020).

Not only the abandoned farmland, about 0.65 million ha of forest is degraded, where a forest-based agroforestry can be promoted by engaging forest users (FRTC 2019). There are successful examples of agroforestry models under the Leasehold Forestry Program (LFP) that allows the leaseholders to cultivate horticultural crops, fodder trees and NTFPs in the forest (Kafley and Pokharel 2017; Khanal et al. 2019). Community forest is another potential avenue for agroforestry promotion in Nepal. It is estimated that the potential community forest area is 5.5 million ha, out of which only 2.3 million ha of forest have come under the CBFM regime (Pathak et al. 2017). These CBFM areas provide the opportunity for experimenting different kind of forest-based agroforestry models which may help increase the overall forest productivity and generate employments for forest users.

9.9.3 Scope of Carbon Credits Under the Market-Based and PES Mechanisms

Agroforestry is a globally accepted climate change mitigation and adaptation strategy. The agroforestry farmers can benefit by selling the carbon stored in trees and soil. The carbon sequestered under this land-use system can be traded in the international markets. Some market-based mechanisms such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and voluntary C markets have recognised agroforestry as eligible land use for C credits (Holmes et al. 2017; Sharma et al. 2016b). In addition to possibility of international trade of carbon, the Forests Act-2019 of Nepal has provisioned payments for environmental services (PES) from trees in its Article 44. According to the article, the private tree growers are eligible to claim for dividends for environmental services including C sequestration if they complete the prescribed conditions (MoFE 2019). This provision could be a motivating factor for farmers to shift to agroforestry from modern intensive agriculture.

9.10 Way Forward/Conclusions

Even though agroforestry has the potential of meeting both livelihood and environmental needs, it is not getting as much attention as it deserves. Some traditional forms of agroforestry are common in Nepal, which has no commercial value.

Improved agroforestry practices are out of the reach of small-holder farmers not because they are not interested but because they are unable to afford it because of high upfront and transaction costs, and lack of enough land. Even the large-scale farmers consider it a risky affair because of poor market infrastructure, middlemen-controlled market mechanism and bureaucratic hassles. Therefore, improved agroforestry has not been a mainstream farming practice in Nepal.

The policy environment has improved after the endorsement of the NAFP in 2019 and has become favourable for agroforestry promotion and expansion in Nepal. The policy has pointed out the way forward for the development and research of such promising land use. Unfavourable legislation and regulations that contradict the agroforestry policy must be amended. Agroforestry needs to be mainstreamed in all sub-sectors, forests, agriculture and livestock. A coordinated effort is recommended to motivate forest user groups for agroforestry adoption in community forests and leasehold forests. A robust institutional setup is necessary at all levels—from central to local levels—that could establish coordination with stakeholders of agroforestry like researchers, farmers, extension workers and industries for information sharing and technology and knowledge transfer. Since Nepal has a diverse climate, soil and socio-economy, location-specific and economically viable agroforestry models need to be developed. Agroforestry has enormous potential of providing environmental and ecosystems services. These services should be quantified and monetised so that more farmers are attracted to agroforestry adoption. Farmers' profits could be maximised by selecting and practising appropriate agroforestry models and involving farmers in a simplified (low transaction cost) carbon crediting mechanism such as REDD+.

Even though the new agroforestry policy is encouraging news for farmers, the division of the same land use into three categories as private forest, agroforest and family forest by the NFP-2018 has created confusion among farmers. In substance, there is no difference between the three because they are all associated with agriculture. Therefore, bringing the other two entities (family forest and private forest) under the agroforestry sub-sector could be a better option to avoid further ambiguity. Mapping agricultural lands suitable for growing trees under agroforestry systems would help to scale up agroforestry across the country. To this end, Ahmad et al. (2021) modelled and mapped cropland areas suitable for planting trees in agroforestry systems in Nepal for the first time across the country. Their study revealed that 83% of rainfed cropland areas exhibit more than 60% tree suitability, which could be harnessed for scaling of agroforestry practices.

References

Acharya B, Dhakal SC (2014) Profitability and major problems of coffee production in Palpa District, Nepal. Int J Appl Sci Biotechnol 2(4):460–463

Acharya S, Sharma SR, Upreti BR, Matthys ML (2021) Why Nepal's main agricultural export product, large cardamom, does not reach the world market. SN Bus Econ 1(1):1–21

Adesina AA, Chianu J (2002) Determinants of farmers' adoption and adaptation of alley farming technology in Nigeria. Agrofor Syst 55(2):99–112

Adhikari S, Ranabhat NB (2011) Bee flora in mid hills of Central Nepal. J Plant Sci 8:45–56

Adhikari S, Baral H, Nitschke C (2018) Adaptation to climate change in Panchase Mountain ecological regions of Nepal. Environments 5(3):42

Ahmad F, Uddin MM, Goparaju L, Dhyani SK, Oli BN, Rizvi J (2021) Tree suitability modelling and mapping in Nepal: a geospatial approach to scaling agroforestry. Model Earth Syst Environ 7(1):169–179

Al-Wabel MI, Hussain Q, Usman AR, Ahmad M, Abduljabbar A, Sallam AS, Ok YS (2018) Impact of biochar properties on soil conditions and agricultural sustainability: a review. Land Degrad Dev 29(7):2124–2161

Amatya SM, Cedamon E, Nuberg I (2018) Agroforestry systems and practices in Nepal. Sopan Press Pvt. Ltd., Dillibazar, Kathmandu, pp 37–57

Andres C, Comoé H, Beerli A, Schneider M, Rist S, Jacobi J (2016) Cocoa in monoculture and dynamic agroforestry. In: Lichtfouse E (ed) Sustainable agriculture reviews. Springer, Cham, pp 121–153

Apuri I, Peprah K, Achana GTW (2018) Climate change adaptation through agroforestry: the case of Kassena Nankana West District, Ghana. Environ Dev 28:32–41

Atreya K, Subedi BP, Ghimire PL, Khanal SC, Charmakar S, Adhikari R (2021) Agroforestry for mountain development: prospects, challenges, and ways forward in Nepal. Arch Agri Environ Sci 6(1):87–99

Bajracharya RM, Shrestha HL, Shakya R, Sitaula BK (2015) Agro-forestry systems as a means to achieve carbon co-benefits in Nepal. J For Livelihood 13(1):59–68

Behera RN, Nayak DK, Andersen P, Måren IE (2016) From jhum to broom: agricultural land-use change and food security implications on the Meghalaya Plateau, India. Ambio 45(1):63–77

Bhandari RP, Joshi R, Paudel D (2021) Agroforestry practices for climate change adaptation and its contribution to farmers' income. J Nat Resour 4(3):42–51

Bhatt YR (2013) Implication of agroforestry system for soil carbon sequestration and livelihood in the Mid-hills of Nepal. M. Sc. Thesis, Norwegian University of Life Sciences, Norway

Biggs EM, Tompkins EL, Allen J, Moon C, Allen R (2013) Agricultural adaptation to climate change: observations from the Mid-Hills of Nepal. Clim Dev 5(2):165–173

Budhathoki NK, Paton D, Lassa JA, Bhatta GD, Zander KK (2020) Heat, cold, and floods: exploring farmers' motivations to adapt to extreme weather events in the Terai region of Nepal. Nat Hazards 103(3):3213–3237

Cedamon E, Nuberg I, Pandit BH, Shrestha KK (2018) Adaptation factors and futures of agroforestry systems in Nepal. Agrofor Syst 92(5):1437–1453

Cedamon ED, Nuberg I, Mulia R, Lusiana B, Subedi YR, Shrestha KK (2019) Contribution of integrated forest-farm system on household food security in the mid-hills of Nepal: assessment with EnLiFT model. Aust For 82(Sup1):32–44

Charles RL, Munishi PKT, Nzunda EF (2013) Agroforestry as adaptation strategy under climate change in Mwanga District, Kilimanjaro, Tanzania. Int J Environ Prot 3(11):29–38

Dagar JC (2018) Perspectives of vegetation ecology and biodiversity for management of ravine lands. In: Dagar JC, Singh AK (eds) Ravine lands: greening for livelihood and environmental security. Springer, Singapore, pp 69–118

Dagar JC, Singh AK (eds) (2018) Ravine lands: greening for livelihood and environmental security. Springer, Singapore, p 636

Dagar JC, Gupta SR, Teketay (eds) (2020) Agroforestry for degraded landscapes: recent advances and challenges, vol 1 and 2. Springer, Singapore

Dahal GR, Pandit BH, Shah R (2020) Abandoned agricultural land and its reutilisation by adoption of agroforestry: a case study from Kaski and Parbat Districts of Nepal. J For Livelihood 19:1–15

Dhakal A (2013) Evolution, adoption, and economic evaluation of an agroforestry-based farming system with and without carbon values: the case of Nepal. Ph. D. Thesis, University of Southern Queensland, Queensland, Australia

Dhakal A, Rai RK (2020) Who adopts agroforestry in a subsistence economy?—Lessons from the Terai of Nepal. Forests 11(5):565
Dhakal A, Cockfield G, Maraseni TN (2012) Evolution of agroforestry-based farming systems: a study of Dhanusha District, Nepal. Agrofor Syst 86(1):17–33
Dhakal A, Cockfield G, Maraseni TN (2015) Deriving an index of adoption rate and assessing factors affecting adoption of an agroforestry-based farming system in Dhanusha District, Nepal. Agrofor Syst 89(4):645–661
FAO (2013) Improving governance of forest tenure—a practical guide. Food and Agriculture Organization, Rome
Feliciano D, Ledo A, Hillier J, Nayak DR (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254:117–129
FRTC (2019) Agroforestry system and practices in Terai and Mid-hills of Nepal. Forest Research and Training Centre (FRTC), Ministry of Forests and Environment, Kathmandu
Ghimire R, Dhungana S (2021) Comparative advantage of *Areca* nut over rice in Jhapa, Nepal. Rev Food Agric 2(1):09–15
Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28(3):97–122
Holmes I, Kirby KR, Potvin C (2017) Agroforestry within REDD+: experiences of an indigenous Emberá community in Panama. Agrofor Syst 91(6):1181–1197
ICIMOD (2019) Sustainable production and marketing of large cardamom: the role of transboundary cooperation in harnessing comparative advantages in the Kanchenjunga Landscape. International Centre for Integrated Mountain Development, Kathmandu. https://lib.icimod.org/recor d/34637. Accessed 25 Oct 2021
IPCC (2007) Climate change: climate change impacts, adaptation and vulnerability, summary for policymakers. Intergovernmental Panel on Climate Change
IPCC (2021) Climate Change 2021—the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press
Jaquet S, Schwilch G, Hartung-Hofmann F, Adhikari A, Sudmeier-Rieux K, Shrestha G, Liniger HP, Kohler T (2015) Does outmigration lead to land degradation? Labour shortage and land management in a western Nepal watershed. Appl Geogr 62:157–170
Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76:1–10
Joshi B, Joshi GR (2016) Factors influencing the adoption of large cardamom-based agroforestry system in the Eastern hills of Nepal. Res J Agric For Sci 4(10):1–10
Kafle SK (2006) Reclamation of flood-damaged areas through agroforestry: a case study from Nepal. In: Proceedings of fourth disaster risk management practitioners' workshop for Southeast Asia, Bangkok, pp 8–10
Kafley GP, Pokharel K (2017) Pro-poor leasehold forestry: a community-based tenure regime in Nepal. J For Livelihood 15(1):43–56
Kalauni D, Joshi A (2019) Production economics, marketing, and critical success factors of Large Cardamom in Bhojpur, Nepal. Cogent Food Agric 5(1):1701358
Karki YK, Regmi PP, Thapa RB (2018) Coffee production in Kavre and Lalitpur Districts, Nepal. J Nep Agric Res 4:72–78
KC S, Upreti BR (2017) The political economy of cardamom farming in eastern Nepal: crop disease, coping strategies, and institutional innovation. SAGE Open 7(2):2158244017705422
KC S, Upreti BR, Subedi BP (2016) We know the taste of sugar because of cardamom production: links among commercial cardamom farming, women's involvement in production and the feminization of poverty. J Int Women's Stud 18(1):181–207

Kebebew Z, Urgessa K (2011) Agroforestry perspective in land use pattern and farmers coping strategy: experience from southwestern Ethiopia. World J Agric Res 7(1):73–77
Khanal D, Gautam D, Bhandari J, Bhattarai S, Gahatraj G, Jandug CMB, Baral K (2019) Contribution of leasehold forestry to users' household income in Sahidlakkhan Rural Municipality, Gorkha, Nepal. North Am Acad Res 2(9):142–152
Kim DG, Kirschbaum MU, Beedy TL (2016) Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: synthesizing available data and suggestions for future studies. Agric Ecosyst Environ 226:65–78
Koirala S, Shakya S, Shrestha G, Adhikari M (2021) Exploring migration and disaster nexus. South Asianist J 8:10–40
Kumar BM, Sikka AK (2014) Agroforestry in South Asia: glimpses from Vedic to present times. Indian Farming 63(11):2–5
Li P, Feng Z, Jiang L, Liao C, Zhang J (2014) A review of swidden agriculture in Southeast Asia. Remote Sens 6(2):1654–1683
Magar LK, Kafle G, Aryal P (2020) Assessment of soil organic carbon in tropical agroforests in the Churiya Range of Makawanpur, Nepal. Int J For Res 2020:8816433. https://doi.org/10.1155/2020/8816433
Maraseni TN, Cockfield G, Apan A (2007) A comparison of greenhouse gas emissions from inputs into farm enterprises in Southeast Queensland, Australia. J Environ Sci Health 42(1):11–18
Maraseni T, An-Vo DA, Mushtaq S, Reardon-Smith K (2020) Carbon smart agriculture: an integrated regional approach offers significant potential to increase profit and resource use efficiency and reduce emissions. J Clean Prod 282:124555
Matthys ML, Acharya S, Khatri S (2021) Before cardamom, we used to face hardship: analyzing agricultural commercialization effects in Nepal through a local concept of the good life. World Dev 141:105410
MoALD (2019) Statistical information on Nepalese agriculture-2018/2019. Ministry of Agriculture and Livestock Development, Kathmandu
MoFE (2019) Forests act-2019. Ministry of Forests and Environment, Kathmandu
MoFSC (2014) Nepal national biodiversity strategy and action plan: 2014–2020. Ministry of Forest and Soil Conservation, Kathmandu
MoPE (2016) Nationally determined contributions. Ministry of Population and Environment, Kathmandu
NAF (2005) Evaluation of NAF-supported agroforestry projects in the mid-hills of Nepal. Nepal Agroforestry Foundation, Kathmandu
NAFP (2019) National Agroforestry Policy-2019. Ministry of Agriculture and Livestock Development (MoALD), Kathmandu
Nair PKR (1993) An introduction to agroforestry. Kluwer Academic Publishers, Dordrecht
Nair PKR (2007) The coming of age of agroforestry. J Sci Food Agric 87(9):1613–1619
Nair PKR, Garrity D (2012) Agroforestry research and development: the way forward. In: Nair PKR, Garrity D (eds) Agroforestry: the future of global land use. Advances in agroforestry, vol 9. Springer, Dordrecht, pp 515–531
Neupane RP, Thapa GB (2001) Impact of agroforestry intervention on soil fertility and farm income under the subsistence farming system of the middle hills, Nepal. Agric Ecosyst Environ 84(2):157–167
Neupane RP, Sharma KR, Thapa GB (2002) Adoption of agroforestry in the hills of Nepal: a logistic regression analysis. Agrofor Syst 72(3):177–196
Ohler FMJ (2000) The impact of leasehold forestry on livelihoods and environment. Food and Agriculture Organization, FAO Representation Office, Kathmandu
Pandey D, Ojha RB, Chalise D, Das S, Twanabasu B (2019) Spatial variability of soil properties under different land use in the Dang district of Nepal. Cogent Food Agric 5(1):1600460
Pandit BH, Neupane RP, Sitaula BK, Bajracharya RM (2013) Contribution of small-scale agroforestry systems to carbon pools and fluxes: a case study from middle hills of Nepal. Small-Scale For 12(3):475–487

Pandit BH, Shrestha KK, Bhattarai SS (2014) Sustainable local livelihoods through enhancing agroforestry systems in Nepal. J For Livelihood 12(1):47–63
Pandit J, Dutta JP, Regmi PP, Shakya SM (2015) Production and marketing of organic coffee in Nepal. J Inst Agric Anim Sci 33–34:91–100
Pandit BH, Nuberg I, Shrestha KK, Cedamon E, Amatya SM, Dhakal B, Neupane RP (2018) Impacts of market-oriented agroforestry on farm income and food security: insights from Kavre and Lamjung districts of Nepal. Agrofor Syst 93(4):1593–1604
Pandit BH, Nuberg I, Shrestha KK, Cedamon E, Amatya SM, Dhakal B, Schmidt HP (2020) Revitalising agrarian economies: the use of biochar on banana-based agroforestry system in Nepal's hills. J For Livelihood 19:17–31
Panth BP, Bhattarai N, Baral P, Karki M, Bhattarai A, Sapkota S (2021) Factors affecting the profitability from goat farming in Gulmi, Nepal. Cogent Food Agric 7(1):1963928
Pathak BR, Yi X, Bohara R (2017) Community based forestry in Nepal: status, issues and lessons learned. Int J Sci 6(3):119–129
Paudel P, Rimal S, Ghimire P, Parajuli K (2019) Agroforestry for enhancing adaptation of local community against drought in hilly region of Nepal. Int J Agric Innov Res 7(4):440–445
Quandt A (2020) Contribution of agroforestry trees for climate change adaptation: narratives from smallholder farmers in Isiolo, Kenya. Agrofor Syst 94(6):2125–2136
Rani S, Rantanoo R, Phogat M, Beniwal S, Kumar S (2018) Monoculture: ecological implications in Indian agriculture. In: Singh J, Hasan W, Nigam N, Tiwari P, Jakhar SR (eds) Integrated farming system: the future of agriculture. Weser Brooks, Germany, pp 112–125
Raut N, Sitaula BK, Bajracharya RM (2010) Agricultural intensification: linking with livelihood improvement and environmental degradation in mid-hills of Nepal. J Agri Environ 11:83–94
Ray DK, West PC, Clark M, Gerber JS, Prishchepov AV, Chatterjee S (2019) Climate change has likely already affected global food production. PLoS One 14(5):e0217148
Regmi BN (2003) Contribution of agroforestry for rural livelihoods: a case of Dhading District, Nepal. In: International conference on rural livelihoods, forests and biodiversity, pp 19–23
Santos PZF, Crouzeilles R, Sansevero JBB (2019) Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic forest. For Ecol Manag 433:140–145
Schick A, Wieners E, Schwab N, Schickhoff U (2018) Sustainable disaster risk reduction in mountain agriculture: agroforestry experiences in Kaule, mid-hills of Nepal. In: Mal S, Singh RB, Huggel C (eds) Climate change, extreme events and disaster risk reduction. Springer, Cham, pp 249–264
Schwab N, Schickhoff U, Fischer E (2015) Transition to agroforestry significantly improves soil quality: A case study in the central mid-hills of Nepal. Agric Ecosyst Environ 205:57–69
Sharma R, Xu J, Sharma G (2007) Traditional agroforestry in the eastern Himalayan region: land management system supporting ecosystem services. Trop Ecol 48(2):189–200
Sharma S, Dhakal CK, Ghimire B, Rijal A (2016a) Economic significance of coffee (*Coffee arabica*) production in Parbat district of Nepal. Int J Agric Manag 6(2):123–130
Sharma R, Chauhan SK, Tripathi AM (2016b) Carbon sequestration potential in agroforestry system in India: an analysis for carbon project. Agrofor Syst 90(4):631–644
Sherchan R, Rai RK, Rai R, Dhakal A (2021) Designing a community-based insurance scheme to reduce human–wildlife conflict. Environ Dev Sustain 24:5112–5130
Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11:368
Shrestha RK (2002) Various patterns of retaining trees in indigenous agroforestry practices in the mid-hills of Nepal. Banko Janakari 12(1):35–41
Shrestha BM, Sitaula BK, Singh BR, Bajracharya RM (2004) Soil organic carbon stocks in soil aggregates under different land use systems in Nepal. Nutr Cycl Agroecosyst 70(2):201–213
Shrestha J, Prasai HK, Timsina KP, Shrestha KP, Pokhrel D, Poudel K, Yadav M (2018) Large cardamom in Nepal: production practice and economics, processing, and marketing. Nepal Agricultural Research Council (NARC), Kathmandu

Singh AK, Arunachalam A, Ngachan SV, Mohapatra KP, Dagar JC (2014) From shifting cultivation to integrating farming: experience of agroforestry development in the north-eastern Himalayan region. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and environmental services. Advances in agroforestry series, vol 10. Springer, pp 57–86

Soni ML, Subbulakshmi V, Yadava ND, Dagar JC (2017) Agroforestry for increasing farm productivity in water-stressed ecologies. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 369–411

Spencer JE (1966) Shifting cultivation in Southeastern Asia. University of California Press, Berkeley

Thapa B, Pande KR, Khanal B, Marahatta S (2018) Effect of tillage, residue management and cropping system on the properties of soil. Int J Appl Sci Biotechnol 6(2):164–168

Tiwari K, Sitaula B, Nyborg I, Paudel G (2008) Determinants of farmers' adoption of improved soil conservation technology in a middle mountain watershed of central Nepal. Environ Manage 42(2):210–222

Tuladhar A, Khanal DR (2018) Coffee production in Nepal—a brief review. In: Drew R, Han Z (eds) Beverage crops. Proceedings of II International Symposium, International Society for Horticulture Science (ISHS), Belgium, pp 161–166

Uddin K, Shrestha HL, Murthy MSR, Bajracharya B, Shrestha B, Gilani H, Pradhan S, Dangol B (2015) Development of 2010 national land cover database for Nepal. J Environ Manage 148:82–90. https://doi.org/10.1016/j.jenvman.2014.07.047

Warren-Thomas E, Dolman PM, Edwards DP (2015) Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. Conserv Lett 8(4):230–241

Zhang J, Jia G, Liu Z, Wang D, Yu X (2019) *Populus simonii* Carr. reduces wind erosion and improves soil properties in Northern China. Forests 10(4):315

Part III
Biodiversity and Ecosystem Services

Chapter 10
The Role of Agroforestry Systems for Enhancing Biodiversity and Provision of Ecosystem Services in Agricultural Landscapes in Southeast Asia

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Abstract Biodiversity has a pivotal role to play in providing ecosystem goods and services, which is under threat due to various anthropogenic activities. This chapter

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is based on literature review to assess the role of agroforestry to enhance biodiversity and ecosystem services in Southeast Asian agricultural landscapes. The reviewed literature was analysed through narrative qualitative and narrative comparative methods. The review provides substantial evidence that agroforestry systems can conserve species diversity and enhance ecosystem services. Farmers' cultivating diverse species in agroforestry is the key to enhance biodiversity on farmlands that can also lessen the pressure on local forest. Careful agroforestry plantation design will not only increase the multiple ecosystem functions but can also create corridors and buffer zones to support natural habitats, to reduce human and wildlife conflict. The case of human conflicts with Asian elephants is an obvious example. From ethical ground to support elephant's right to survive, further research on agroforestry modelling is required to benefits both humans and elephants.

Keywords Tree-based farming · Species diversity · Conservation · Ecosystem services · Asian elephant

10.1 Introduction

Biological diversity is crucial for ecosystem functioning and its services (Isbell et al. 2015). Biodiversity successively supports ecosystem goods and services, which include production of raw materials for consumption and production (provisioning services); carbon sequestration, control of pests and diseases and climate regulation (regulating services); nutrient cycling and crop pollination (supporting services) and spiritual and recreational values (cultural services) (Mori et al. 2017, see Fig. 10.1). However, biodiversity in many places in Southeast Asia is now under threat mainly due to anthropogenic disturbances, e.g. agricultural expansion, deforestation and overexploitation of natural resources, which has significant negative impact to ecosystem services and associate climate (Udawatta et al. 2021; Coelho et al. 2020). Furthermore, such biodiversity loss can undermine the capacity to create biological materials (biocapacity), thus affect millions of living organisms in which their lives rely on (Zari and Pedersen 2014).

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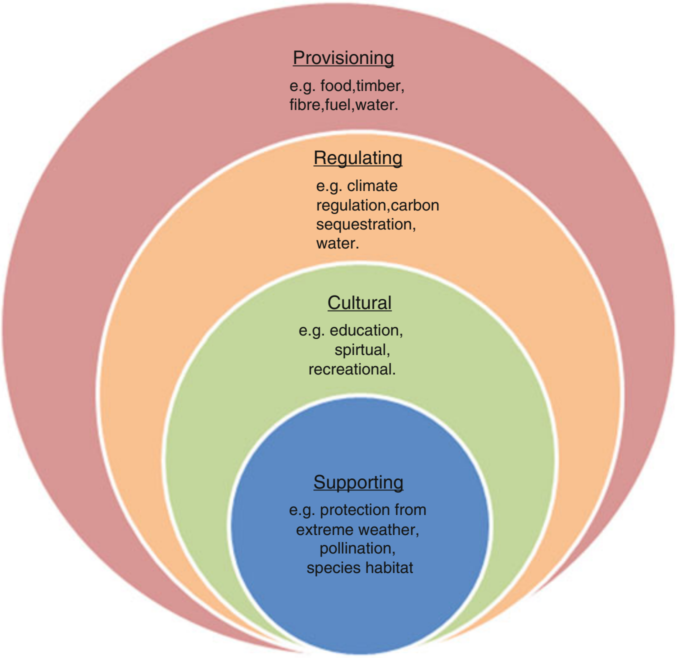


Fig. 10.1 Four types of ecosystem services. (Adapted from Mori et al. (2017)

Agroforestry can be an effective tool to preserve species diversity and to improve the ecosystem functions and services due to many reasons: (1) it supports natural interactions between various species living in the same area and offers habitat for certain disturbance-tolerant species, (2) it conserves soil from erosion and support purifying water that prevent habitat degradation and loss, contributing to biodiversity conservation, (3) it increases vegetation structure and variants that can help with nutrient cycling and biodiversity enhancement, without sacrificing farm production and (4) it can function as a habitat corridor for area-sensitive plant and animal species (Kumar 2016; Udawatta et al. 2019). However, still much to know about the role of agroforestry to conserve species diversity, especially in the agricultural landscapes in Southeast Asia.

Large mammal, i.e. elephants, can be best protected in a place where protected areas are surrounded by buffer zones and connected by corridors (Nyhus and Tilson 2004). In that sense, complex agroforestry systems can promote multifunctional buffer zones to provide livelihood and conservation benefits for people and wildlife.

Globally, agroforestry accounts for more than one billion hectares or about 43% of agricultural land (Santos et al. 2019). As over two billion hectares of degraded land exist globally, it can give opportunity to rehabilitate some of this land through agroforestry to fulfil the livelihood needs of constantly growing population, while reducing the negative impact to biodiversity and environment (Duffy et al. 2021; Dagar et al. 2020). A well-designed agroforestry consists of suitable species can potentially restore the degraded land, and to increase ecosystem functions and biodiversity (Siarudin et al. 2021; Martin et al. 2020; Rahman et al. 2019). The objective of this chapter is to synthesize the role of agroforestry systems to enhance biodiversity and ecosystem services provisions in Southeast Asian agricultural landscapes.

10.2 Materials and Methods

This chapter is based on a literature review (using peer-reviewed and grey literature) to assess the role of agroforestry to enhance biodiversity and ecosystem services in Southeast Asian agricultural landscapes. After selecting keywords and phrases, prospective scientific literature was collected from Web of Science, Google Scholar and Scopus. After removing duplicates, we have selected 48 of the 522 published literature for extensive review following their relevance. A total of 5 months from June to October 2021 were spent to extract the data.

The selected keywords and search phrases of this study include ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’, ‘agroforestry’ AND ‘biodiversity’ AND ‘Southeast Asia’, ‘agroforest’ AND ‘biodiversity’ AND ‘Southeast Asia’, ‘tree based farming’ AND ‘biodiversity’ AND ‘Southeast Asia’, ‘agroforestry’ AND ‘ecosystem services’ AND ‘Southeast Asia’, ‘agroforest’ AND ‘ecosystem services’ AND ‘Southeast Asia’, ‘tree based farming’ AND ‘ecosystem services’ AND ‘Southeast Asia’, ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’ AND ‘income’, ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’ AND ‘job creation’, ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’ AND ‘species’, ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’ AND ‘benefit’, ‘agroforestry’ OR ‘agroforest’ OR ‘tree based farming’ OR ‘alley cropping’ OR ‘mix tree crops planting’ AND ‘habitat’, ‘Asian elephants’, ‘plant species’ AND ‘Asian elephant’, ‘tree planting’ AND ‘Asian elephant’, ‘agroforestry’ AND ‘Asian elephant’. The inclusion criteria of our literature search were scientific information of agroforestry systems to enhance biodiversity and ecosystem services in the Southeast Asian agricultural landscapes.

The analysis methods—narrative comparative and narrative qualitative—were used to interpret collected information following the objective of this chapter. A careful attention was paid through a process of decontextualization and recontextualization to represent the objectivity of the view of reality.

10.3 Synthesis

10.3.1 Agroforestry and Biodiversity Conservation

Agroforestry systems have a crucial role to conserve biodiversity (Table 10.1), and providing ecosystem services. There are at least three major benefits of agroforestry to conserve biodiversity, i.e. (1) providing supportive species habitat that tolerate to a certain level of disturbance; (2) maintaining natural habitat existence across the landscapes (in certain conditions, see also Rahman et al. 2017) and (3) creating permeable and more benign 'matrix' of habitats that can support the integrity of these remnants and the conservation of their populations (Schroth et al. 2004).

Agroforestry systems increase biological diversity on farm lands by cultivating diverse species that can also provide supporting roles to conserve nearby natural habitats (Rahman et al. 2017; Mcneely and Schroth 2006). Empirical research has provided evidence that there are a range of species, i.e. trees (timber, fruits, nuts, spices), cereals and oil seed crops, vegetables and herbs, cultivating in the agroforestry systems in Indonesia (Rahman et al. 2016; Michon 2005). The jengkol agroforest in Ogan Komering Ilir, South Sumatra (Fig. 10.2), or damar agroforests in Pesisir, Lampung or durian agroforests in Jambi and Palembang, are rich in biodiversity (Rahman 2017; Rahman et al. 2016; Michon 2005). Furthermore, research conducted in West Java and West Sumatra, Indonesia (Rahman et al. 2017; Murniati et al. 2001), and in Mindañao, the Philippines (Garrity et al. 2002) found the link between increased agroforestry practices and conserving local forest biodiversity by reducing pressure on local forest. This is because, through tree-based climate smart farming, agroforestry can provide potential alternatives of many important forest products (e.g. fruits, vegetables, herbs, spices, firewood, timber and fodder) that are important for local livelihoods (Rahman 2017; Snelder and Lasco 2008; Michon 2005). However, some challenges faced by farmer, i.e. land, labour and capital, may determine the capacity of agroforestry to reduce deforestation (Angelsen and Kaimowitz 2004).

Therefore, with such qualities, agroforestry systems can gain further importance in an international political level in a view of the Convention on Biological Diversity (CBD), which has emphasized resource management through ecosystem approaches, including conservation, equitable sharing and sustainable use of benefits (Mcneely and Schroth 2006).

10.3.2 Agroforestry and Ecosystem Services

Agroforestry systems help improving ecosystem functions through enhanced delivery of various services. Table 10.2 is showing the list of services provided by different agroforestry systems in Southeast Asia.

Table 10.1 Various species conservation provided by agroforestry systems in Southeast Asia

Country	Agroforestry type	Species	Diversity measure	Note	Reference
Indonesia	Rubber- and fruit-based agroforestry	Mammals	Sumatran tiger and Sumatran elephant	Agroforestry farms, which are located outside core protected areas can play pivotal role as a buffer zone to protect Sumatran tiger and elephant	Nyhus and Tilson (2004)
Indonesia	Coffee- and fruit-based agroforestry	Insects	Bees	Plant species in this agroforestry system attract 20 species of bees that can also facilitate pollination and farm yield	Klein (2003)
Thailand	Rubber- and other tree-based agroforestry	Birds, insects and reptiles	Varies types of birds, butterflies and reptiles	Butterfly richness was found in this agroforestry system. However, such richness was increased with greater natural forest extent. Bird and reptile richness was similar between agroforestry and monocultures, but bird richness increased with the height of herbaceous vegetation inside rubber plots.	Warren-Thomas et al. (2019)
Indonesia	Cacao agroforestry	Birds	Varies types of birds	Shade trees are critical for bird conservation in cacao agroforestry system	Clough et al. (2009)
Malaysia	Oil palm with coconut and other fruits	Birds	Varies types of birds	Polyculture practices support diversity of bird species that provide vital ecosystem services such as pest control, pollination and seed dispersal	Atiqah et al. (2019)

(continued)

Table 10.1 (continued)

Country	Agroforestry type	Species	Diversity measure	Note	Reference
Malaysia	Mixed fruit orchard	Small mammals	Bats and non-volant	Less intensively managed agroforestry, i.e. mixed fruit orchard, support habitat of bats and other non-volant species	Baqi et al. (2020)
Indonesia	Mixed tree-based system	Plant	Timber, fruits, nuts and spice trees	Agroforestry system can increase and conserve tree species diversity in a landscape scale	Rahman (2017), Rahman et al. (2016), Michon (2005), Murniati et al. (2001), Garrity et al. (2002)
Indonesia and the Philippines	Mixed tree-based system	Plant	Fruits, vegetables, herbs, spices, timber, firewood and fodder	Agroforestry system can increase species diversity in a landscape scale	Snelder and Lasco (2008), Michon (2005)

Fig. 10.2 Damar agroforest in Pesisir Lampung (left), and jengkol agroforest in Ogan Komering Ilir, South Sumatra (right). (Photo © Michon (2005) (left) and Muhardianto Cahya (right))

Enhancing ecosystem services through agroforestry can also increase farm income and create jobs for the rural communities (Rahman 2011). In the Philippines (Cagayan de Oro), cultivating trees (i.e. *Gliricidia sepium*) with fodder grasses

Table 10.2 Various ecosystem services provided by agroforestry systems in Southeast Asia

Country	Agroforestry type	Ecosystem services	Reference
Vietnam	Homegardens	*Provisioning services* Peanut, rice paddy, hill rice, vegetables, sugarcane, cassava, maize, mango, grapefruit, custard apple, longan *Supporting services* Income generation, nutrition	Hoang et al. (2017)
Vietnam	Berry + coffee- based agroforestry	*Provisioning services* Berry, coffee *Supporting services* Improving soil fertility, reducing soil erosion, enhancing biodiversity	Nguyen et al. (2020)
Vietnam	Fruit tree-based agroforestry	*Provisioning services* Longan, maize, guinea grass, mulato grass *Supporting services* Reducing soil erosion, enhancing soil moisture and fertility, weed control *Cultural services* Women empowerment	Do et al. (2020)
Thailand	Fruit + rubber-based agroforestry	*Provisioning services* Wood, timber, jackfruit, rambutan, coconut, pineapple, banana, vegetables *Supporting services* Diversity of plants, birds, reptiles and butterflies	Warren-Thomas et al. (2019)
Malaysia	Agrosilvicultural and silvopastoral	*Provisioning services* Wood, timber, meat *Supporting services* Soil conservation, soil fertility	Musa et al. (2019)
Indonesia	Cocoa + durian + langsat-based agroforestry	*Provisioning services* Cocoa, fruits *Regulating services* Climate regulation *Supporting services* Enhancing biodiversity	Sari et al. (2020)
Indonesia	Cocoa complex agroforestry (cocoa, fruit tree, sandalwood, bitti, cananga and white teak tree	*Provisioning services* Cocoa, fruits, wood, timber *Regulating services* Carbon storage, water regulation	Sari et al. (2020)
Indonesia	Rattan + timber tree-based agroforestry	*Provisioning services* Food-young juvenile of rattan, timber, fuelwood	McShane and Wright (2020)
Indonesia	Rubber + durian + gaharu-based agroforestry	*Provisioning services* Rubber, gaharu wood, durian,	

(continued)

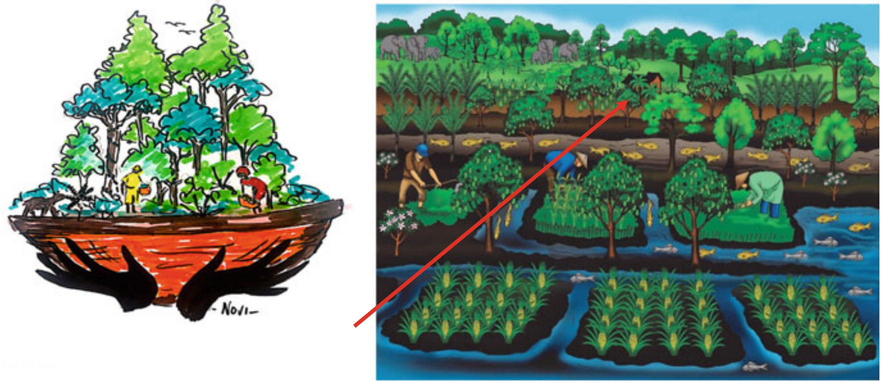
Table 10.2 (continued)

Country	Agroforestry type	Ecosystem services	Reference
		bamboo *Regulating services* Hydrological function *Supporting services* Soil erosion control, biodiversity	Insusanty et al. (2018)
Philippines	Cocoa-based agroforestry	*Regulating services* Carbon storage	Lasco et al. (2001)
Philippines	Multi-storey agroforestry system	*Provisioning services* Coffee, cocoa, mango, durian, lanzones, mangosteen, marang, jackfruit, rambutan *Regulating services* Carbon sequestration, water regulation *Supporting services* Soil erosion control, biodiversity	Palma et al. (2020)

helped people to enhance their income from the production of livestock, as well as reduce farm labour from herding (FAO 2005). In Central and Eastern Java, Indonesia, creating 'living savings account' through developing tree cultivation on farm lands, supported costs of temporary migration of young people to the cities to generate further family income (Roshetko et al. 2008). Local people also consider agroforestry systems as a crucial mechanism that can diversify farm production, enhance household income and reduce livelihood related risk (Schuren and Snelder 2008). Therefore, even agroforestry has lesser capacity in delivering many ecosystem services per land area compared to forests, the value of agroforestry systems remain crucial as the global forest resources are under pressure and human population is expanding (Snelder and Lasco 2008; Roshetko 2013).

*10.3.3 Agroforestry for Mitigating Conflict Between Human and Asian Elephants (*Elephas maximus*)*

Asian elephants roam in China, Nepal, India, Sri Lanka, Bangladesh, Bhutan, Myanmar, Laos, Thailand, Vietnam, Cambodia, Malaysia (Malay Peninsula and Borneo) and Indonesia (Sumatra and Borneo) (Williams et al. 2020). Much of their habitats are in areas with dense human population, and therefore experiencing threats from major anthropogenic land conversions (Williams et al. 2020). Furthermore, elephant habitat fragmentation has caused their population to decline (Williams et al. 2020). Land expansion, including agriculture, has also increased conflict intensity and frequency between human and elephants (Shaffer et al. 2019). Both elephants and



(a) (b)

Fig. 10.3 Agroforestry systems, (**a**) layers of canopies of various species mimicking complex forests ecosystem (image illustrated by Novi Nugraheni, University of British Columbia); (**b**) sharing agroforestry land with elephants for their free movement in the buffer zone (image illustrated by Komaruddin, CIFOR)

humans may receive negative consequences from the conflict (Sampson et al. 2021; Wilson et al. 2013).

As agroforestry is widely practised in Southeast Asia (Rahman 2017; Kumar et al. 2012; Michon 2005), and many of them mimic the complexity of natural forest structure (Young 2017), it can potentially benefit both human and wildlife (Fig. 10.3). Elephants are notably known as an umbrella species, where their presence is important for ecosystem health (Kuswanda and Barus 2017). Asian elephants also act as a seed dispersal agent (Campos-Arceiz and Blake 2011). Tan et al. (2021) found that at least 25 flora families receive benefits from elephants as their disbursement agent. Absence of mammals, particularly the seed dispersal type, such as elephants, could hamper germination of many plant species, thus creation of forest (Redford 1992).

Land-use change has caused an impact on elephant's movement (Erot et al. 2020), including an increasing frequency of crop raiding in the community land (Anuradha et al. 2019). This is due to the lack of food for elephants in the destroying forests (Yamamoto-Ebina et al. 2016). To prevent crop raiding, many communities plant species which are disliked by elephants, such as chilli pepper (Hedges and Gunaryadi 2010). However, such strategy could further irritate hungry elephants desperately looking for food and create more conflict (Mumby and Plotnik 2018).

Therefore, one of the feasible strategies is to combine species with careful plantation design that will not only include species disliked by elephants but also edible for them, on a communal or public lands that the local people are willing to share with elephants (list of potential edible and non-edible species for elephants are provided in the Annex). Furthermore, Nyhus and Tilson (2004) have explored the idea to promote a buffer zone between agricultural land and protected areas, using suitable species in well-designed agroforestry systems that can benefit both human and elephants (Fig. 10.3). Therefore, it can be useful to follow-up such idea, not only from ecological but also from social perspective. Further research on the modelling of appropriate agroforestry systems in different landscapes could bring benefits both for human and elephants.

10.4 Conclusions

This chapter explored the potential of agroforestry systems to enhance biodiversity and ecosystem services, particularly in the agricultural landscapes of Southeast Asia. Based on the literature review, it is concluded that agroforestry systems can potentially contribute to biodiversity conservation through habitat provision, lowering the rates of natural habitat conversion and forming benign and permeable habitat remnants. Cultivating diverse species in agroforestry systems is the key to increase biodiversity on farmlands. In addition, combining agricultural and forestry species can also lessen the pressure on local forest, since these are the substitute for essential forest products, e.g. fruits, vegetables, herbs, firewood, fodder and timber to local communities. It is also concluded that agroforestry systems can improve the provision of ecosystem services in the agricultural landscape. There are various ecosystem services that can be provided by agroforestry systems, e.g. soil fertility and erosion control, climate and water regulation, carbon storage and social safeguarding. These enhancements can potentially translate into increased income and job opportunities. It is further concluded that agroforestry systems have the potential to mitigate conflicts between humans and wildlife. To ensure the survival of Asian elephants, further studies are needed to identify agroforestry models and policy instruments that maintain harmony and welfare of local communities and elephant populations.

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Annex (Tables 10.3 and 10.4)

Table 10.3 List of edible plants for elephant

Family	Species
Alangiaceae	*Alangium javanicum*[a]
Amaranthaceae	*Amaranthus spinosus*[b]
Anacardiaceae	*Pentaspadon motleyi*., *Spondias dulcis*[c] *Lannea coromandelica*, *Mangifera indica*, *Spondias pinnata*[b]
Annonaceae	*Cananga odorata, Miliusa velutina*[b]

(continued)

Table 10.3 (continued)

Family	Species
Apocynaceae	*Alstonia pneumatophora*[d] *Holarrhena antidysenterica, Wrightia arborea*[b]
Araceae	*Colocasia gigantea*[d]
Arecaceae	*Calamus* sp., *Daemonorops angustifolius, Salacca conferta*[d] *Licuala* sp., *Arenga* sp.[a] *Calamus areborescens, Caryota* sp.[e] *Salacca zalacca*[b]
Asteraceae	*Eupatorium odoratum, Mikania cordata, Tithonia diversifolia*[d]
Bambucaceae	*Bambusa* spp.[d]
Bignoniaceae	*Heterophragma adenophyllum, Markhamia stipulata*[b]
Bombacaceae	*Durio zibethinus*[d]
Boraginaceae	*Cordia dichotoma, Cordia grandis*[b]
Burseraceae	*Santiria laevigata, Dacryodes rostrata*[d]
Burseraceae	*Garuga pinnata*[b]
Caesalpinaceae	*Bauhinia malabarica, Bauhinia scandens, Cassia fistula*[b]
Callophylaceae	*Calophyllum* sp.[c]
Combretaceae	*Terminalia bellirica*[b]
Convolvulaceae	*Merremia hederacea*, *Merremia vitifolia*[b]
Costaceae	*Costus speciosus*[a] *Costus speciosus*[b]
Cyperaceae	*Cyperus rotundus*, *Cyperus aromaticum*[e] *Cyperus* sp., *Cyperaceae* sp.[b]
Cycadaceae	*Cycas siamensis*[b]
Davalliaceae,	*Nephrolepis exaltata*[d]
Dilleniaceae	*Dillenia excelsa*[b] *Dillenia arbiflos*[c] *Dillenia excelsa* (Jack) Gilg[a] *Dillenia indica* L., *Dillenia parviflora* Griff[b]
Dipterocarpaceae	*Shorea* sp., *Hopea dryobalanoides* Miq[d]
Euphorbiaceae	*Macaranga javanica*[e] *Mallotus paniculatus, Macaranga pruinosa, Macaranga gigantea, Macaranga tanarius, Aporosa mycrocalyx*[c] *Mallotus muticus*[a] *Croton oblongifolius, Mallotus cochinchinensis*[b]
Fabaceae	*Pueraria phaseoloides*[d] *Intsia bijuga*[c] *Butea superb, Dalbergia oliveri, Dalbergia ovata*, *Dalbergia volubilis, Millettia extensa, Mucuna pruriens*[b]
Flacourtiaceae	*Flacourtia ramontchi*[b]
Gleicbeniaceae	*Gleichenia linearis*[d]
Guttiferae	*Garcinia mangostana, Garcinia parvifolia*[d]
Hernandiaceae	*Hernandia ovigera*[d]
Icacenaceae	*Stemonurus scorpioides*[c]
Lauraceae	*Litsea* sp.[d]
Lecythidaceae	*Careya arborea*[b]

(continued)

Table 10.3 (continued)

Family	Species
Linaceae	*Ixonanthes icosandra*[c]
Lythraceae	*Lagerstroemia tomentosa*[b]
Malvaceae	*Ceiba pentandra*[d]
Marantaceae	*Donax canniformis*[a]
Marattiaceae	*Angiopteris evecta*[d]
Melastomaceae	*Melastoma malabathricum*[d] *Memecylon* sp.[a]
Meliaceae	*Cedrela serrata*[b]
Menispermaceae	*Tinospora nudiflora*[b]
Mimosaceae	*Albizzia falkata, Mimmosa pudica*, *Parkia speciosa*[d] *Pithecellobium dulce*[c] *Acacia concinna, Acacia megaladena*, *Acacia pennata, Albizia chinensis, Entada pursaetha*, *Neptunia* sp., *Samanea saman, Xylia xylocarpa*[b]
Moraceae	*Artocarpus heterophyllus, Artocarpus kemando, Artocarpus elasticus*[d] *Ficus benjamina*[c] *Antiaris toxicaria, Ficus auriculata, Ficus cunia*, *Ficus glomerata*, *Streblus asper*[b]
Musaceae	*Musa laterita*[b]
Myrtaceae	*Syzygium* sp.[a]
Oleaceae	*Jasminum multiflorum*[b]
Onagraceae	*Ludwigia adscendens*[b]
Rutaceae	*Aegle marmelo*[b]
Pandanaceae	*Pandanus* sp., *Pandanus terrestris*[d]
Phyllanthaceae	*Bridelia stipularis*[a]
Poaceae	*Ichnanthus vicinus*, *Imperata cylindrica, Setaria geniculata, Paspalum conjungatum, Digitaria ciliaris, Cynodon dactylon, Ottochloa nodosa, Hymenachne amplexicaulis*[d] *Chrysopogon aciculatus, Panicum repens, Imperata cylindrica*[e] *Paspalum conjugatum*[c] *Phragmites karka, Dinochloa scabrida*[a] *Bambusa bambos, Bambusa burmanica, Bambusa polymorpha, Cephalostachyum pergracile, Eragrostis japonica, Oryza sativa, Phragmites vallatoria, Themeda intermedia*, *Thysanolaena maxima*[b]
Polygalaceae	*Irvingia malayana*[c]
Rubiaceae	*Coffea canephora*[c] *Gardenia elata*[a] *Gardenia turgida, Mitragina rotundifolia*, *Morinda angustifolia*, *Paederia foetida*[b]
Salicaceae	*Scolopia spinosa*[d]
Sapindaceae	*Pometia pinnata, Nephelium lapaceum*[d] *Nephelium cuspidatum* var. *robustum*[c] *Lepisanthes fruticosa*[a]
Sapindaceae	*Mischocarpus pentapetalus*[b]
Sapotaceae	*Palaquium burckii*[c]
Smilaceae	*Smilax macrophylla*[b]

(continued)

Table 10.3 (continued)

Family	Species
Sterculiaceae	*Heritiera fomes*[d]
Theaceae	*Archboldiodendron calosericeum*[d]
Thymeleaceae	*Aquilaria* sp.[d]
Tiliaceae	*Grewia hirsuta*, *Grewia humilis*[b]
Verbenaceae	*Vitex pubescens, Peronema canescens*[d] *Gmelina arborea, Tectona grandis, Vitex leucoxylon*[b]
Zingeberaceae	*Achasma megalocheilas*[d] *Alpinia aquatica*, *Nicolaia speciosa, Curcuma* sp.[c] *Alpinia ligulata*[a] *Amomum corynostachyum*[b]

[a] English et al. (2014)
[b] Campos-Arceiz et al. (2008)
[c] Wardana et al. (2017)
[d] Syarifuddin (2008)
[e] Hamdani et al. (2018)

Table 10.4 List of non-edible plants for elephant

Family	Species
Arecaceae	*Caryota mitis, Arenga* sp., *Pinanga sp.*[a]
Euphorbiaceae	*Aleurites moluccana*[b]
Lamiaceae	*Pogostemon cablin*[b]
Malvaceae	*Theobroma cacao*[b]
Rubiaceae	*Coffea arabica*[b]
Solanaceae	*Capsicum frutescens*[b]

[a] Suba et al. (2020)
[b] Berliani et al. (2018)

References

Angelsen A, Kaimowitz D (2004) Is agroforestry likely to reduce deforestation? In: Schroth G, Da Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac AN (eds) Agroforestry and biodiversity conservation in tropical landscapes. Island Press, London, pp 87–106

Anuradha JMPN, Fujimura M, Inaoka T, Sakai N (2019) The role of agricultural land use pattern dynamics on elephant habitat depletion and human-elephant conflict in Sri Lanka. Sustainability 11(10):2818. https://doi.org/10.3390/su11102818

Atiqah N, Yahya MS, Aisyah S, Ashton-Butt A, Azhar B (2019) Birds associated with different tree species and structures in oil palm agroforestry landscapes in Malaysia. Emu-Austral Ornithol 119(4):397–401

Baqi HMA, Iqbal NM, Nabilah AN, Aiman ANA, Suganthi A, Fong PH, Jayaraj VK (2020) The diversity of small mammals in a mixed fruit orchard at Bukit Bekong limestone massif, Merapoh, Pahang, Malaysia. IOP Conf Ser Earth Environ Sci 596(1):012073

Berliani K, Alikodra HS, Masy'ud B, Kusrini MD (2018, 2015) Food preference of Sumatran elephant *(Elephas maximus sumatranus)* to commodity crops in human-elephant conflict area of Aceh, Indonesia. J Phys Conf Ser 1116(5)

Campos-Arceiz A, Blake S (2011) Mega-gardeners of the forest—the role of elephants in seed dispersal. Acta Oecol 37(6):542–553

Campos-Arceiz A, Lin TZ, Htun W, Takatsuki S, Leimgruber P (2008) Working with mahouts to explore the diet of work elephants in Myanmar (Burma). Ecol Res 23:1057–1064

Clough Y, Dwi PD, Pitopang R, Tscharntke T (2009) Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. Biol Conserv 142(5):1032–1041

Coelho AJP, Magnago LFS, Matos FAR, Mota NM, Diniz ÉS, Meira-Neto JAA (2020) Effects of anthropogenic disturbances on biodiversity and biomass stock of Cerrado, the Brazilian Savanna. Biodivers Conserv 29(11):3151–3168

Dagar JC, Gupta SR, Teketay D (eds) (2020) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1 and 2. Springer, Singapore

Do VH, La N, Mulia R, Bergkvist G, Dahlin AS, Nguyen VT, Pham HT, Öborn I (2020) Fruit tree-based agroforestry systems for smallholder farmers in Northwest Vietnam—a quantitative and qualitative assessment. Land 9(11):451

Duffy C, Toth GG, Hagan RPO, McKeown PC, Rahman SA, Widyaningsih Y, Sunderland TCH, Spillane C (2021) Agroforestry contributions to smallholder farmer food security in Indonesia. Agrofor Syst 95:1109–1124. https://doi.org/10.1007/s10457-021-00632-8

English M, Gillespie G, Ancrenaz M, Ismail S, Goossens B, Nathan S, Linklater W (2014) Plant selection and avoidance by the Bornean Elephant (*Elephas maximus borneensis*) in tropical forest: does plant recovery rate after herbivory influence food choices? J Trop Ecol 30(4): 371–379

Erot LP, Mutinda M, Mutinda MN (2020) Land use and cover changes and their effects on elephant home ranges and distribution in Mara Landscape, Narok County, Kenya. Afr J Ecol Ecosyst 7(2):1–15

FAO (2005) State of the world's forests 2005. FAO, Rome

Garrity D, Amoroso VB, Koffa S, Catacutan D, Buenavista G, Fay P, Dar W (2002) Landcare on the poverty–protection interface in an Asian watershed. Conserv Ecol 6(1):12

Hamdani F, Yoza D, Oktorini Y (2018) Feed palatability Sumatran Elephant (*Elephas Maximus Sumateranus Temminck*.) in Gondai Village base Langgam District Pelalawan Regency Riau Province. JOM Faperta UR 5(1)

Hedges S, Gunaryadi D (2010) Reducing human-elephant conflict: do chillies help deter elephants from entering crop fields? Oryx 44(1):139–146

Hoang LT, Roshetko JM, Huu TP, Pagella T, Mai PN (2017) Agroforestry-the most resilient farming system for the hilly Northwest of Vietnam. Int J Agric Syst 5(1):1–23

Insusanty E, Ikhawan M, Sadjati E (2018) Agroforestry models in Riau Main Island Indonesia: Kampar Regency Context. IOP Conf Ser Earth Environ Sci 156(1):012063

Isbell F, Tilman D, Polasky S, Loreau M (2015) The biodiversity-dependent ecosystem service debt. Ecol Lett 18(2):119–134

Klein A (2003) Pollination of Coffea canephora in relation to local and regional agroforestry management. J Appl Ecol 40(5):837–845

Kumar V (2016) Multifunctional agroforestry systems in the tropics region. Nat Environ Pollut Technol 15(2):365–376

Kumar BM, Singh AK, Dhyani SK (2012) South Asian agroforestry: traditions, transformations, and prospects. In: Nair PKR, Garrity D (eds) Agroforestry—the future of global land use (Advances in agroforestry book series), vol 9. Springer, pp 359–389

Kuswanda W, Barus SP (2017) Diversity and determination of wildlife 'Umbrella species' in the Gunung Leuser National Park. Jurnal Penelitian Kehutanan Wallacea 6(2):113–123

Lasco RD, Sales RF, Estrella R, Saplaco SR, Castillo AS, Cruz RVO, Pulhin FB (2001) Carbon stocks assessment of two agroforestry systems in the Makiling Forest Reserve, Philippines. Philipp Agric Sci 84(4):401–407

Martin DA, Osen K, Grass I, Hölscher D, Tscharntke T, Wurz A, Kreft H (2020) Land-use history determines ecosystem services and conservation value in tropical agroforestry. Conserv Lett 13(5):e12740

Mcneely JA, Schroth G (2006) Agroforestry and biodiversity conservation: traditional practices, present dynamics, and lessons for the future. Biodivers Conserv 15:549–554

McShane P, Wright W (2020) Ethnobotany, rattan agroforestry, and conservation of ecosystem services in Central Kalimantan, Indonesia. Agrofor Syst 94(2):639–650

Michon G (ed) (2005) Domesticating forests: how farmers manage forest resources. IRD, CIFOR and ICRAF, Bogor

Mori AS, Lertzman KP, Gustafsson L (2017) Biodiversity and ecosystem services in forest ecosystems: a research agenda for applied forest ecology. J Appl Ecol 54(1):12–27

Mumby HS, Plotnik JM (2018) Taking the elephants' perspective: remembering elephant behavior, cognition and ecology in human-elephant conflict mitigation. Front Ecol Evol 6:122. https://doi.org/10.3389/fevo.2018.00122

Murniati, Garrity DP, Gintings AN (2001) The contribution of agroforestry systems to reducing farmers' dependence on the resources of adjacent national parks: a case study from Sumatra. Agrofor Syst 52:171–184

Musa F, Lile NA, Hamdan DDM (2019) Agroforestry practices contribution towards socioeconomics: a case study of Tawau Communities in Malaysia. Poljoprivreda I Sumarstvo 65(1): 65–72

Nguyen MP, Vaast P, Pagella T, Sinclair F (2020) Local knowledge about ecosystem services provided by trees in coffee agroforestry practices in Northwest Vietnam. Land 9(12):486

Nyhus P, Tilson R (2004) Agroforestry, elephants, and tigers: balancing conservation theory and practice in human-dominated landscapes of Southeast Asia. Agric Ecosyst Environ 104(1): 87–97

Palma RA, Canencia OP, Tiongco LE, Boniao RD, Florida EJ, Dagonio JY (2020) Agroforestry systems and practices in Hilly Uplands of Misamis Oriental, Philippines. IOP Conf Ser Earth Environ Sci 449(1):012046

Rahman SA (2011) Cost-benefit and livelihood impacts of agroforestry in Bangladesh. Lap Lambert Academic Publishing, Saarbrucken

Rahman SA (2017) Incorporation of trees in smallholder land use systems: farm characteristics, rates of return and policy issues influencing farmer adoption. Ph D Thesis, University of Copenhagen, Denmark and Bangor University, UK

Rahman SA, Sunderland T, Roshetko JM, Basuki I, Healey JR (2016) Tree culture of smallholder farmers practicing agroforestry in Gunung Salak Valley, West Java, Indonesia. Small-Scale For 15(4):433–442

Rahman SA, Jacobsen JB, Healey JR, Roshetko JM, Sunderland T (2017) Finding alternatives to Swidden agriculture: does agroforestry improve livelihood options and reduce pressure on existing forest? Agrofor Syst 91:185–199

Rahman SA, Baral H, Sharma R, Samsudin YB, Meyer M, Lo M, Artati Y, Simamora TI, Andini S, Leksono B, Roshetko JM, Lee SM, Sunderland T (2019) Integrating bioenergy and food production on degraded landscapes in Indonesia for improved socio-economic and environmental outcomes. Food Energy Secur 8(3):e00165. https://doi.org/10.1002/fes3.165

Redford KH (1992) The empty forest: many large animals are already ecologically extinct in vast areas of neotropical forest where the vegetation still appears intact. Bioscience 42(6):412–422

Roshetko JM (2013) Smallholder tree farming systems for livelihood enhancement and carbon storage. PhD Thesis, Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

Roshetko JM, Snelder DJ, Lasco RD, van Noordwijk M (2008) Future challenge: a paradigm shift in the forestry sector. In: Snelder DJ, Lasco RD (eds) Smallholder tree growing for rural development and environmental services: lessons from Asia. Advances in agroforestry series, vol 5. Springer, Amsterdam, pp 453–485

Sampson C, Rodriguez SL, Leimgruber P, Huang Q, Tonkyn D (2021) A quantitative assessment of the indirect impacts of human-elephant conflict. PLoS One 16(7):e0253784

Santos PZF, Crouzeilles R, Sansevero JBB (2019) Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. For Ecol Manag 433:140–145

Sari RR, Saputra DD, Hairiah K, Rozendaal D, Roshetko JM, van Noordwijk M (2020) Gendered species preferences link tree diversity and carbon stocks in cacao agroforest in Southeast Sulawesi, Indonesia. Land 9(4):108

Schroth G, Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac AMN (2004) Agroforestry and biodiversity conservation in tropical landscapes. Island Press, Washington, DC

Schuren SHG, Snelder DJ (2008) Tree growing on farms in Northeast Luzon (The Philippines): smallholders' motivations and other determinants for adopting agroforestry systems. In: Snelder DJ, Lasco RD (eds) Smallholder tree growing for rural development and environmental services: lessons from Asia. Advances in agroforestry series, vol 5. Springer, Amsterdam, pp 75–97

Shaffer LJ, Khadka KK, Hoek JVD, Naithani KJ (2019) Human-elephant conflict: a review of current management strategies and future directions. Front Ecol Evol 6:235. https://doi.org/10.3389/fevo.2018.00235

Siarudin M, Rahman SA, Artati Y, Indrajaya Y, Narulita S, Ardha MJ, Larjavaara M (2021) Carbon sequestration potential of agroforestry systems in degraded landscapes in West Java, Indonesia. Forests 12(6):714

Snelder DJ, Lasco RD (2008) Smallholder tree growing in South and Southeast Asia. In: Snelder DJ, Lasco RD (eds) Smallholder tree growing for rural development and environmental services: lessons from Asia. Advances in agroforestry series, vol 5. Springer, Amsterdam, pp 3–33

Suba RB, Beveridge NGP, Kustiawan W, de Snoo GR, de Iongh HH, van Wieren SE, Choi YH, Kim HK (2020) Food preference of the bornean elephant (*Elephas maximus borneensis*) in North Kalimantan Province, Indonesia, and its conservation implications. Raffles Bull Zool 68: 791–802

Syarifuddin H (2008) Preference of Sumatera elephant forage (*Elephas maximus sumatranus*): case study in Seblat area. Jurnal Ilmiah Ilmu-Ilmu Peternakan 11(4):83–92

Tan WH, Hii A, Solana-Mena A, Wong EP, Loke VPW, Tan ASL, Kromann-Clausen A, Hii N, Pura PB, Tunil MTB, Din SAL, Chin CF, Campos-Arceiz A (2021) Long-term monitoring of seed dispersal by Asian elephants in a Sundaland rainforest. Biotropica 53(2):453–465

Udawatta RP, Rankoth LM, Jose S (2019) Agroforestry and biodiversity. Sustainability 11(10): 2879

Udawatta RP, Rankoth LM, Jose S (2021) Agroforestry for biodiversity conservation. In: Agroforestry and ecosystem services. Springer, Cham, pp 245–274

Wardana SA, Yoza D, Oktorini Y (2017) Carrying capacity of feed Sumatran Elephant (*Elephas maximus sumatranus* Temminck) in Tesso Nilo National Park Province of Riau. JOM Faperta Universitas Riau 4(2)

Warren-Thomas E, Nelson L, Juthong W, Bumrungsri S, Brattström O, Stroesser L, Chambon B, Penot É, Tongkaemkaew U, Edwards DP, Dolman PM (2019) Rubber agroforestry in Thailand provides some biodiversity benefits without reducing yields. J Appl Ecol 57(1):17–30

Williams C, Tiwari SK, Goswami VR, de Silva S, Kumar A, Baskaran N, Yoganand K, Menon V (2020) *Elephas maximus*. The IUCN red list of threatened species 2020: e.T7140A45818198. https://doi.org/10.2305/IUCN.UK.2020-3.RLTS.T7140A45818198.en. Accessed 30 Nov 2021

Wilson S, Davies TE, Hazarika N, Zimmermann A (2013) Understanding spatial and temporal patterns of human–elephant conflict in Assam, India. Oryx 49(1):140–149

Yamamoto-Ebina S, Saaban S, Campos-Arceiz A, Takatsuki S (2016) Food habits of Asian elephants *Elephas maximus* in a rainforest of Northern Peninsular Malaysia. Mammal Study 41(3):155–161

Young KJ (2017) Mimicking nature: a review of successional agroforestry systems as an analogue to natural regeneration of secondary forest stands. In: Montagnini F (ed) Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty. Advances in agroforestry, vol 12. Springer, Cham, pp 179–209

Zari MP, Pedersen M (2014) Ecosystem services analysis in response to biodiversity loss caused by the built environment. https://journals.openedition.org/sapiens/1684. Accessed 28 Nov 2021

Chapter 11
Potentials of Indigenous Fruit Trees in Enhancing Nutrition, Income and Biodiversity Conservation in African Agroforestry

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Abstract Indigenous fruit trees are in abundance as wild in the forests of Africa and play very significant role in food, nutrition, income and livelihood security of millions of people, especially the poor in Africa. Many species have been identified for their potential in meeting the nutritional requirement, value addition, income generation and biodiversity conservation when domesticated from the wild. The chemical composition of some of these species have been analysed and found to be rich in nutritional value and show potential for processing as juice, jelly, jam, edible oil and alcoholic beverages. Their uses as fodder, timber and making small tools and medicinal value have been documented but many of these remain underutilized and have potential for domestication and may be explored further when cultivated using proper propagation techniques. These may also play a vital role as sources of commercial products and mitigating climate change by sequestering carbon. Potential of some of the most preferred trees, challenges for their domestication and research needs have been discussed in this article.

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Keywords Indigenous fruit trees · Domestication · Value addition · Nutritional security · Income generation · Biodiversity conservation · Most preferred trees

11.1 Introduction

Indigenous fruit and medicinal trees play a significant role in the food, nutrition, health and incomes of millions of people in Sub-Saharan Africa (Akinnifesi et al. 2008a; Jamnadass et al. 2011; Leakey and Akinnifesi 2008, 2017). Many of these species also provide products with great potential for processing and marketing (Ham et al. 2008). Some species produce fruits out of season and this creates opportunities for the development of cultivars which will extend the season of availability. The 'Noel' cultivar of *Dacryodes edulis* in Cameroon (Leakey et al. 2002) is a good example. There is also a great potential to develop them into tree crops for commercialization through clonal propagation (Leakey and Akinnifesi 2017; Leakey et al. 2017). The role of underutilized fruit and medicinal tree species in combating hunger, malnutrition, disease and poverty becomes more apparent as concerns of climate change and food security increase.

Nevertheless, almost all indigenous fruit tree species are still in a wild or semi-domesticated state and therefore, have remained neglected and underutilized. The reasons for the long neglect of indigenous fruits and failure to domesticate them have been variously identified as due to: (1) lack of information and reliable method for measuring the contribution to rural economy, livelihoods of communities and ecological services; (2) low production incentives relating to markets and technology (e.g. lack of cultivar development); (3) bias in favour of large-scale agriculture and conventional forestry; (4) colonial interventions that left a profound legacy of neglect of smallholder farm production in favour of estate farm producers and European export product trading interests and (5) weak interface between private sector actors, researchers and extension staff in tree products (Akinnifesi et al. 2008b). Although planting of indigenous fruit trees is not a common practice, they are selectively retained when farmers are clearing the land for agriculture (Teklehaimanot 2008; Kalinganire et al. 2008). In other parts of the continent, indigenous fruit trees are continuously being destroyed by an ever-increasing population and demands for new farmlands, human settlements, wood for fuel and construction and forest conversion to agriculture (Teklehaimanot 2008). Indigenous fruit tree species have also not benefitted from positive agricultural or forestry policies, research and extension development (Campbell 1987; Leakey et al. 2017). Most National Agricultural Research Institutions (NARIs) focus on improvement of staple food crops, but research interest on indigenous fruit trees has been lacking. The scientific and development community started to pay attention to underutilized crops only in the 1970s. Even then, the number of international and national programmes involved with indigenous fruit trees has remained very small. Lack of attention to indigenous fruit trees has been compounded by the misconception that they are abundant in the forest. This has been aggravated by the limited understanding of the genetic variability, reproductive biology, propagation techniques, field management requirements, value addition and marketing (Akinnifesi et al. 2006). However, the importance of commercial products from indigenous fruit trees is steadily gaining recognition in both developing and developed country markets (Akinnifesi et al. 2006). As a result, interest in domestication has increased, and a farmer-driven and market-led process is now being implemented in many parts of Africa (Leakey et al. 2003; Simons and Leakey 2004; Akinnifesi et al. 2008a, b, c, d). The indigenous fruit tree domestication efforts aimed at promoting the cultivation of species with economic potential as new cash crops, and providing incentive to subsistence farmers to plant trees on their farms (Akinnifesi et al. 2008b). The low-technology options are more appropriate if the participatory approach to domestication is the preferred strategy. In this case, farmers vegetatively propagate their best trees to create selected cultivars (Leakey and Akinnifesi 2017).

The early history of indigenous fruit tree domestication has been detailed elsewhere (Leakey et al. 2005; Akinnifesi et al. 2008a, b). According to Leakey et al. (2017), more than 420 research papers involving more than 50 tree species have been published on tree domestication over three decades (1992–2012). The first decade was characterized by species assessment, germplasm improvement and dissemination of propagation techniques. The second decade included characterization of genetic variation using morphological and molecular techniques, product commercialization, adoption and impact and farmers' rights, nutrition and composition of marketable products. The third decade focused on the research that underpin agroforestry tree domestication and scaling up, as well as commercialization (Leakey et al. 2017). This chapter briefly describes the human uses and functions of indigenous fruit and nut trees in general, nutritional values of priority species, current research and trends in domestication and commercialization of priority species including more recent developments.

11.2 Human Uses in Different Regions of Africa

Indigenous fruit trees have many uses; primary among them are the edible fruits and nuts. The fruits may be eaten fresh, dry or processed into alcoholic beverages, jam, juice and jellies (Maghembe et al. 1998; Akinnifesi et al. 2008a; Ham et al. 2008; Dagar et al. 2020). Traditional fruits like marula (*Sclerocarya birrea*), monkey oranges (*Strychnos cocculoides, S. spinosa*), bird plum (*Berchemia discolor*), baobab (*Adansonia digitata*), *Diospyros* spp., *Grewia* spp., manketti (*Sciniziophyton rautanenii*), mobola plum (*Parinari curatellifolia*), *Uapaca kirkiana, Vangueria infausta* and many others have become part and parcel of the life of rural population. Ripe fruits of many of the species are consumed as such since immemorial times. For example, marula (*S. birrea* subsp. *coffra*) is known and consumed by humans in southern Africa for millenia (Walker 1989). Monkey oranges are other delicious fruits in Kwango and Caprivi regions in southern Africa. Fruits of *Annona senegalensis, Diospyros mespiliformis, Friesodielsia obovata, Parinnari* *curatellifolia, Securinega virosa, Syzygium cordatum, S. guineense, Vangueria infausta, Vangueriopsis lanciflora, Ximenia americana, Ziziphus mucronata* and *Z. mauritiana* are among many others which are consumed raw when ripe and are highly nutritious.

Depending on their seasonal occurrence, the trees provide an additional dietary supplement during hunger periods in the agricultural cycle. For example, in southern Africa, at least one species is ripe every month, including during the traditional periods of hunger in the agricultural cycle, which occurs in January–February every year (Akinnifesi et al. 2004). Fruits of some of the species appear even in unusually dry periods, and are thus, particularly valuable sources of food and nutrition during emergency periods of food shortage, such as famine, droughts and war (Jama et al. 2007; Teklehaimanot 2008). Because of drought, *Berchemia discolor* is one of the most preferred fruit trees in Katma Mulilo region of Namibia, and *S. rautanenii* (manketi) has been the tree of difficult times in Kavango region. *Balanites aegyptiaca*, prominent in dry regions on all types of soils, is very useful tree bearing highly nutritive fodder and fruits consumed both when ripe and dried. Many parts of the plant are used as famine food in Africa; the leaves are eaten raw or cooked, the oily seed is boiled to make it less bitter and eaten mixed with cereals, and the flowers are also consumed. The tree is considered valuable in arid regions because it produces fruit even in dry period. The fruit can be fermented for refreshing drinks. The seed cake is used as animal feed. Thus, the local communities in drylands heavily rely on these (indigenous fruit trees) resource as emergency food and fodder for livestock. For example, *Cordeauxia edulis* is sometimes the only food left for the nomads during droughts in the arid areas of eastern Ethiopia and Somalia (Teklehaimanot 2008).

Dried kernels or nuts of some species are consumed raw or roasted or made into porridge. For example, dried kernels of marula, manketti; dried fruits of bird plum, *D. mespiliformis, P. curatellifolia*; arils of *Guibourtia coleosperma*; and roasted seeds of *Kigelia africana, Bauhinia thonningii* and *Schotia afra* are consumed making porridge; and dried fruits of *Grewia flava, G. flavescens* and *G. retinervis* are soaked in water, mashed and eaten as porridge. Cooking a mixture of pounded eembe, marula kernels, water and salt makes a traditional cake/bread. Fruits of marula, monkey orange and eenkwiyu (*Ficus sycomorus*) are used in making traditional jam; fruits of *Ximenia caffra* make a tart jelly; fruits of *Grewia* spp mixed with fresh milk to make a kind of yoghurt. Rural people most commonly use manketti and marula oils as edible and a kind of cooking oil is extracted from the fruit of nonzwe (*Ochna pulchra*), which can be stored for about a year.

Most of the fruits mentioned above (marula, manketti kernels, bird plum, monkey orange, *Grewia flava, G. bicolor, Dialium engleranum, Diospyros mespiliformis, Parinari curatellifolia, Garcinia livingstonei* and *Ziziphus mucronata*) are extensively used for preparing alcoholic drinks, which now is also being explored commercially. Fruits of *Adansonia digitata, Syzygium guineense, Dialium engleranum* and arils and red skin of *Guibourtia colosperma* make a kind of refreshing beverage. Young fruits of makami palm (*Hyphaena petersiana*), a sap exuded from spadix of makami palm and wild date palm (*Phoenix reclinata*) is converted into an alcoholic drink. Fruits of *Rhus lancea* pounded with water are fermented for a kind of beer.

Indigenous fruits are also a source of oil for use in cosmetic products (e.g. *Sclerocarya birrea*, *Adansonia digitata*, *Ximenia caffra*) and fuel for cooking, medicinal products, fodder, fibre, timber, saps and resin. Where products and markets have been developed effectively, indigenous fruits have become sources of household incomes and revenue for national economies, as has been documented for several indigenous species such as *Sclerocarya birrea* in South Africa and *Uapaca kirkiana* in Zimbabwe (Akinnifesi et al. 2008a). For example, the fruit pulp and oil of *Adansonia digitata* have gained formal international market in the EU and USA hence an income generation for millions of rural farmers (De Smedt et al. 2011). More than 70 species of indigenous fruit tree species, besides having edible fruits or nuts, have one or more medicinal and other minor uses such as crafting and thatching, fencing, tools and dug-out canoes among local communities (Table 11.1).

In addition, most tree species provide shade, modulate the microclimate, reduce surface run-off, improve water storage, increase soil fertility, carbon sequestration and conserve biodiversity (Bayala et al. 2006, 2014; Teklehaimanot 2008). These effects can increase opportunities for associated crops to thrive especially during drought years. By reducing air temperature, solar radiation and wind velocity, trees decrease potential evapotranspiration under their crown canopies resulting in higher soil moisture contents than in open areas without tree cover. For example, Grouzis and Akpo (1997) recorded temperatures lower by 6 °C under *Balanites aegyptiaca* tree crowns than in direct sunlight. Similarly, Bayala et al. (2014) reported a reduction in the maximum daily temperature by an average of 1–2.5 °C and an increase in the minimum air humidity by up to 5%, with stronger differences on hotter and drier days. Soil temperature was also substantially reduced by at least 5 °C under crowns of *Adansonia digitata* and *Vitellaria paradoxa* (Belsky et al. 1989; Jonsson et al. 1995). Jonsson et al. (1995) found significant reduction in wind speed under *Vitellaria paradoxa* trees compared with the open. Significantly, higher soil moisture has been reported under tree crowns of *B. aegyptiaca* and *V. paradoxa* than in the open (Boffa 1999).

One of the most important functions of indigenous fruit trees on farmland is their contribution to soil organic carbon (SOC), which plays a key role in improvement of soil physico-chemical properties. Mature trees have often been cited as hot-spots of SOC and islands of fertility in drylands (Bayala et al. 2006; Takimoto et al. 2009). SOC is known to contribute to the provision of important supporting ecosystem services including nutrient inputs, enhancement of internal flows and reduction of nutrient losses. Thus, indigenous fruit trees on farmland can play a critical role in Sub-Saharan Africa where loss of SOC is becoming the most limiting factor for soil ecological functions, crop growth and production. In addition, N fixing species such as *Vitex doniana* and *Cordeauxia edulis* may increase soil N availability. However, empirical data are lacking on the amount of N fixed by these tree species and conditions that promote N fixation. Studies based on soil chemical analysis beneath some of the species have shown a common pattern of superior soil fertility under tree canopies than in areas distant from the trees (Bayala et al. 2002; Boffa 1999). For

Table 11.1 Fruit, ethnomedicinal and other minor uses of indigenous fruit trees of Africa

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Adansonia digitata (Bombacaceae)	Baobab, mabuyu, muyu, mukuya	1, 2	Bark as rope and floor mats; light wood for boats; bark used fever, body pain; root used to treat impotency; leaves in kidney and bladder problems, diarrhoea, asthma; fruit made into a drink used to treat fever and scorbutic complaints (Apr–Oct)[b]
Allanblackia floribunda (Cluciaceae)	Tallow tree	3, 5, 7	Wood minor tools; seed oil for soap making; bark and leaf decoction for asthma, bronchitis, diarrhoea, dysentery, toothache (most of the year)
Ancylanthos bainesii (Rubiaceae)	Guwaiadjoadjoa	1	Root infusion for eye pain, headache, chest pain and cough (Oct–Dec)
Annona senegalensis (Annonaceae)	Wild custard apple, mulolo, mukonogwa	1	Roots for dizziness and claimed to cure madness (Oct–Dec)
Annona stenophylla (Annonaceae)	Duih	1	Roots for tooth pain (Feb–March)
Azanza garckeana (Malvaceae)	Snot apple Moneko	1	Inner bark fibre for ropes; fruit without seeds chewed as gum (Feb–Sep)
+*Balanites aegyptiaca* (Zygophyllaceae)	Desert date	1, 5, 7	Seed as famine food; leaves good fodder; bark decoction used as spasmolytic, antodote to arrow poison; leaves in worm infection, liver and spleen disorders; fruit in dysentery and constipation; seed in tumour and wounds, as laxative, in stomach ache, fever, to treat syphilis, haemorrhoid, jaundice, yield cortistone drug (April–June)
Bauhinia petersiana (Caesalpineaceae)	White bauhinia, koffiebeeskloa	5	Leaves as remedy for common cold, seed used substitute to coffee (Feb–May)
Bauhinia thonningii (Caesalpineaceae)	Camel's foot, monkey bread	5	Bark as fibre; green fruit as soap substitute; all parts medicinal (June–Sept)
+*Berchemia discolor* (Rhamnaceae)	Bird plum, embee, voelpruim, mukumba, muzinzia	1, 2, 3, 4, 6	A dye from inner bark; good forage and firewood (Jan–May)
Carissa edulis (Apocynaceae)	Simple spined num-num	1, 3	Root and fruit as flavouring; root to relieve pain in arthritis, rheumatism, as vermifuge (Oct–Dec)
Cassine aethiopica (Celastraceae)	Kooboo-berry	1	Bark infusion as drench for worm infestation in calves (June–Jan)
	Transvaal saffron wood	1	Bark infusion to relieve stomach ache and fever; wood for cattle trough,

(continued)

Table 11.1 (continued)

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Cassine transvaalensis (Celastraceae)			spoons, ladles and tobacco pipes (Jun–Nov)
Chrysophyllum caimito (Sapotaceae)	Star apple	1, 3	Bark medicinal (Feb–Apr)
Cordeauxia edulis (Caesalpiniaceae)	Vehib	1, 2, 5	Leaves yield red dye and are medicinal (June–July)
+*Dacryodes edulis* (Burseraceae)	African plum, bush butter, safou	1, 2, 5, 7	Fodder; seed oil in food industry, as medicinal in yellow fever, diarrhoea, anaemia, skin diseases, wounds (Nov–Mar)
Detarium microcarpum (Fabaceae)	Detar, Bambara, ntamajalan	1, 3, 6	All parts medicinal, root used as mosquito repellent (Sep–Jan)
Dialium engleranum (Caesalpiniaceae)	Kalahari pod berry, nonsimba, nonsisibe, muhamani	2, 4, 6	Attracts bees; crushed wood as disinfectant; root decoction for dysentery; cooked bark for stomach ache; leaf infusion for cough and chest pains (Dec–June)
Diospyros batocana (Ebenaceae)	Sand jackal berry, mufumbo	1	Hard wood for spoons and small carvings; leaves as enema (overdose fatal) (Sept–Feb)
+*Diospyros mespiliformis* (Ebenaceae)	Ebony diospyros, muchenje, mupako	1, 4, 6	Wood to make canoes, furniture, flooring, stamping blocks; bark, twigs and leaves remedy for ringworm, leprosy, wounds, fever and dysentery (Apr–Sept)
+*Dovyalis caffra* (Salicaceae)	Kei-apple		Root and thorn used in chest pain, amenorrhoea; bark and root in rheumatism (Dec–May)
Ehretia rigida (Boraginaceae)	Puzzle bush	1	Powdered roots applied to cuts and to treat gall-sickness in cattle (Oct–Jan)
Erythrococca menyharthii Euphorbiaceae	Northern red berry	1	Leaves used as vegetables, fodder; medicinal (Dec–Jan)
Euclea divinorum (Ebenaceae)	Diamond-leaved euclea, magic guarri	1	Wood for minor tools; bark yields brown dye; fruit taken as aperient and used in brewing beer and make a purple ink (Oct–Dec)
Euclea pseudebenus (Ebenaceae)	Ebony tree, ebbeboom, trawib	1	Wood timber, fire wood; root infusion for head ache and toothache (Feb–May)
Euclea undulata (Ebenaceae)	Common guarri, thicket euclea	1	Root remedy for tooth ache and heart ailments, is purgative; bark for head ache; leaves good fodder (Apr–Oct)

(continued)

Table 11.1 (continued)

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Ficus carica (Moraceae)	Domestic fig, ng/kchau	1, 6	Leaves fodder, fruit medicinal (Apr–May)
Ficus sycomorus (Moraceae)	Sycomore fig, katema, mukuyu, muchaba	1	Infusion of bark and latex used for chest and glandular complaints, diarrhoea and inflamed throat (July–Dec)
Flacourtia indica (Flacourtiaceae)	Flacouria, goewerneursprium	1, 2	Root decoction for body pain; dry leaves tonic and used for asthma and decoction to treat screw-worm in cattle (Jan–June)
Friesodielsia obovata (Annonaceae)	Bastard dwaba berry	1, 2, 3, 5, 6	Wood for small tools; root decoction used for treating stomach-ache, infertility in women and as an antidote for snakebite
+*Garcinia kola* (Cluciaceae)	Bitter kola	1, 5, 6, 7	Fruit and seed in body pain, fever, asthma, cough, throat infections and tuberculosis (July–Sept)
+*Garcinia livingstonei* (Cluciaceae)	Mangosteen, Imbe, mukwananga, mungindu, mutungwa	1, 6	Root used as aphrodisiac; Leaf and flower extracts show antibiotic properties (Nov–Dec)
Grewia avellana (Tiliaceae)	Muchaba, mundumdu	1, 6	Root remedy to sore eyes, diarrhoea and stomach ache (Sep–Oct)
Grewia bicolor (Tiliaceae)	Bastard, false brandy bush, kapopo	1, 6	Plant fibre for ropes, twigs for bows and arrows; fruits for local drink *machao* and *epoaka*; roots for chest complaints (Mar–June)
Grewia falcistipula (Tiliaceae)	Gloai, gloach	1	Roots part of other drug used as contraceptive (Mar–June)
Grewia flava (Tiliaceae)	Brandy bush, wilderosyntjie	1, 4, 6	Bark fibre for baskets; twigs nused as tooth brush; heavily browsed by game and stock (Dec–Apr)
Grewia flavescens (Tiliaceae)	Donkey berry	1	Roots for stomach troubles (Mar–June)
Grewia schinzii (Tiliaceae)	Zambezi raisin, omushe, mutulu	1, 3, 6	Fruit used to make a beer and to treat heart burn (Apr–June)
Grewia tenex (Tiliaceae)	Small leaved white cross-berry	1	Plant for bone fracture and tissue healing; fruit for promoting fertility in women and as a special diet to pregnant women and anaemic children (Feb–June)
Grewia villosa (Tiliaceae)	Mallow raisin	1, 2	Root to treat body pain, wounds, syphilis; dry fruit for stomach ache (Apr–May)
Guibourtia coleosperma (Caesalpiniaceae)	False mopane, nonsivi, mushibi, muzauli,	4, 5, 6	Wood for furniture, tools, crafts, firewood; bark yields a dye; bark and leaves to treat cough and healing wounds (May–July)

(continued)

Table 11.1 (continued)

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Hexalobus monopetalus (Annonaceae)	Shakama plum	1, 2, 5	Wood for timber; bark fibre; fruit extract shows bioactive anti-fungal activities (Dec–Apr)
Hyphaene petersiana (Arecaceae)	Itala palm, makami	1, 2, 6	Branches for furniture, tools, crafts, firewood; leaf fibre for mats, baskets and ropes; leaves as thatching material; root and kernel for dry cough (Sep–Oct)
Irvingia gabonensis (Irvingiaceae)	Bush mango	1, 3, 7	Wood as timber; leaves as fodder; kernels used as condiment, in sauces, cakes, seed oil in soaps; bark as medicinal in hernia, yellow fever, dysentery, diarrhoea, antidote to poison (Apr–Jul; Sep–Oct)
Kigelia africana (Bignoniaceae)	Sausage tree, worsboom, munguh	5, 6	Wood for making boxes and dugout canoes; bark and fruit in stomach ailments; powdered fruit for dressing ulcers and sores (Dec–June)
+*Mimusops zeyheri* (Sapotaceae)	Transvaal red milk wood	1	Bark to treat ulcers, wounds; leaves to treat diabetes; root to treat syphilis, stomach ache, gynaecological disorders (Apr–Sep)
Myrica serrata (Myricaceae)	Lauce leafy berry, lauce-leaved wax-berry	1	Branches to get fat rich in fatty acids; fruit rich in vit C and with stem and leaves produce aromatic oil (Apr–Oct)
Ochna pulchra (Ochnaceae)	Peeling plane, peeling bark ochna	1, 7	Wood for kitchen utensils; Seeds yield un-pleasant smelling poisonous oil, in Zambia it is used for cooking and soap making; bark used to treat burns, wounds and diarrhoea (Jan–March)
Olea europaea (Oleaceae)	Wild olive	1	Bark infusion relieves colic; leaf decoction used for sore throat (Mar–July)
Oncoba spinosa (Flacourtiaceae)	Snuff box tree, mulangu	1	Drying seed oil for varnishes; root used in dysentery and bladder complaints (Apr–Jul)
Pappea capensis (Sapindaceae)	Indaba tree, doppruim	1, 3, 6	Seed oil for soap making and lubrication and edible with mild purgative action, remedy for ringworm and to restore hair; bark used to treat venereal diseases; root infusion given to cattle as a purge; leaf infusion to cure sore eyes (Feb–July)
+*Parinaria curatellifolia* (Chrysobalanaceae)	Mobola plum, mubula	1, 4, 6	As a hot fomentation from bark used to treat pneumonia, cataracts, earache; leaves applied in dislocated and broken bones, wound healing and pneumonia (Oct–Jan)

(continued)

Table 11.1 (continued)

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Parkia biglobosa (Mimosaceae)	Nere	2, 5	Leaves good fodder; seed used as spice and medicinal, fruit rich in vitamin C
Phoenix reclinata (Arecaceae)	Wild date palm, chisonga, mukapakapa	1, 6	Leaves as thatching material, sap from spadix make intoxicating drink (Feb–Apr)
Salvadora persica (Salvadoraceae)	Mustard tree, regte mosterd boom	1	Leaves fodder; Seed oil used in soap making (Sept–Feb)
+*Schinziophyton (Ricinodendron) rautanenii* (Euphorbiaceae)	Manketti, mongongo, nongongo	4, 5, 6	Wood for canoes, carving, crafts and utensils; bark for stomach pain, diarrhoea and helpful drink for pregnant women who feel sick (Feb–Sept)
*Schotia afra (*Caesalpiniaceae)	Karoo boer-bean	5	Bark to treat heart burn and hangovers (Oct–March)
+*Sclerocarya birrea* (Anacardiaceae)	Marula, maroela, mulula, muongo	1, 2, 3, 5, 6	Bark to treat dysentery, diarrhoea and to prevent malaria, given to pregnant women to have a child of desired sex; leaves in intestinal and constipation problems (Feb–March)
Securinega virosa (Euphorbiaceae)	Snow berry, katoma	1	Root infusion with a meat broth is taken in malaria and considered effective in snakebite; bark for treatment of diarrhoea and pneumonia (Dec–March)
+*Strychnos cocculoides* (Loganiaceae)	Cork bark monkey orange, maguni	1,2, 3, 6	Roots of young tree given to children to treat stomach ache, also given in cold, cough; bark decoction and juice of unripe fruit used in stomach pain, malaria; unripe fruit pounded in water used in snakebite and swellings and juice applied to treat ear pain. (Mar–Sept)
Strychnos pungens/ spinosa (Loganiaceae)	Spine-leaved monkey orange, tha, matu	1,2,3,6	Used as above (July–Dec)
Strychnos spinosa (Loganiaceae)	Spiny monkey orange, groen klapper	1, 2, 3	Roots in cough, gonorrhoea, malaria; pounded leaf applied for healing wounds and neck pain (Mar–Sept)
Syzygium cordatum (Myrtaceae)	Water berry/lily, umdoni, mutuya	1, 2, 6	(Nov–Apr)
+*Syzygium guineense* (Myrtaceae)	Woodland water berry, water peer	1, 6	Wood for dug-out canoes; root infusion to bathe a patient with serious illness; bark in chest complaints (Nov–Apr)
+*Tamarindus indica* (Fabaceae)	Tamarind	1, 2, 3	Wood in timber; leaves fodder; fruit medicinal

(continued)

Table 11.1 (continued)

Species (Family)	English/African name	Fruit uses[a]	Medicinal and other minor uses and fruit availability[b]
Uapaca kirkiana (Rubiaceae)	Wild loquat/medlar		Root and bark used in dysentery, indigestion and intestinal problems; leaves used as fodder (Jan–Apr)
+*Vangueria infausta* (Rubiaceae)	Wild medlar, mubilo, ibbu, guri	1,4	Root a remedy for malaria, roundworm, chest pain and pneumonia; leaves applied in animals to tick bite spots and wounds (Jan–Apr)
Vangueriopsis lanciflora (Rubiaceae)	False wild medlar, muhole, mumbole	1, 2, 6	Wood for making utensils, charcoal and as wood fire; root and bark used to purify blood and heart ailments and dysentery (Sept–Jan)
+*Vitellaria paradoxa* (Sapotaceae)	Shea, karite	5, 7	Butter prepared from nut used in chocolates, pharmaceuticals (Jun–Aug)
Vitex doniana (Lamiaceae)	Bluck plum	1	Leaves as fodder and are medicinal; seed oil used in skin creams
Vitex mombassae (Lamiaceae)	Smell-berry vitex, poerabessie	1	Wood for tool handles, fuel; root decoction for diabetes, infertility and as antiemetic; fruit rich in vit C (Jan–June)
Vitex pavos (Lamiaceae)	Chocolate berry	1	Root for stomach ailments; bark to treat threadworm, skin problems; leaf decoction as appetiser (Feb–June)
Ximenia americana (Olacaceae)	Small blue sour plum, mulutulua	1, 6	Seed oil used to soften leather and as cosmetic; inner root bark to treat wounds and in infant maladies (Dec–Feb)
Ximenia caffra (Olacaceae)	Large sour plum, musambya	1, 3	Leaf decoction in inflamed eyes; seed oil for chapped feet and wounds; roasted and mashed seed applied to hair for colouring dark black and straighten it (Dec–Jan)
+*Ziziphus mauritiana* (Rhamnaceae)	Ber	1, 2, 3, 7	Fire wood; charcoal; leaves good fodder; bark medicinal
+*Ziziphus mucronata* (Rhamnaceae)	Buffalo thorn, mukalu	1, 6	The stock and game browse the leaves and fruit; root decoction for treating diarrhoea, coughing blood and tuberculosis; leaf paste used to cure boils and other skin infections (Mar–Aug)

Source: Compiled by Dagar (2003) from various sources, mainly Palgrave (1983), Leger (1997), Ayuk et al. (1999b), and Omotayo and Aremu (2020)

[a] Fruit uses depict as: 1 = fruit consumed when ripe, 2 = fruit juice or refreshing beverage, 3 = used in jam, jellies, 4 = stored dry and made into porridge, 5 = seed edible, ground into meal, 6 = alcohol, 7 = edible seed oil

[b] In parenthesis months indicating the period of availability of fruits in wild

example, Bayala et al. (2002) found higher SOC, total phosphorus (P) and potassium (K) under *Vitellaria paradoxa* and *Parkia biglobosa* crown than in the open in the Sahel. Similarly, Belsky et al. (1989) recorded higher soil N, P, K and calcium (Ca) contents under crowns of *Adansonia digitata* than in the open area in East Africa. Improvement in microclimatic conditions under trees can enhances soil microbial activity, organic matter decomposition and soil physical characteristics. For example, Belsky et al. (1989) reported 35–60% higher soil microbial biomass-carbon, lower bulk density of top soil, and higher water infiltration rates under *Adansonia digitata* crowns than in the open. Trees can intercept wind-blown soil particles and deposit them in the soil by throughfall and stemflow. Species such as *Balanites aegypitica, Cordeauxia edulis*, *Tamarindus indica* and *Ziziphus mauritiana* may play an important role in intercepting dust as they retain their leaves during dry season when most soil laden winds prevail in drylands. For example, according to Roose and co-workers (cited in Boffa 1999) rainwater collected under *Vitellaria paradoxa* canopies had higher concentrations of N, P, K, C, Ca and Mg than in the open. The inclusion of indigenous fruit trees in production systems can reduce the risks inherent to monocultures of staple food crops, such as insect and disease outbreaks, soil nutrient depletion and reliance on a single crop for income (Haq et al. 2008). Some species have mystical and religious significance in some societies and are used for spiritual ceremonies (Haq et al. 2008).

In the following sections, examples of the human uses of indigenous fruit trees will be illustrated using selected priority species in different parts of Africa. These species have been identified based on farmer participatory selection for a particular uses, producers and consumers. In most cases, trees providing food particularly edible fruits and nuts dominated farmers' choices among species. In addition to fruits, some also provide edible leafy vegetables and medicinal products, timber and animal fodder. For brevity, we will focus on selected species that were chosen by farmers for their fruits and nuts, and we will describe the priority species in each region of Africa.

11.2.1 West and Central Africa

The humid tropical region of West and Central Africa includes the Congo Basin which is the world's second largest continuous rainforest after the Amazon. Over 70 species of indigenous fruit trees have been identified and efforts in domestication are on-going (Franzel et al. 2008; Leakey et al. 2017). Systematic work started in 1998 initially focusing on species in the humid lowlands of Cameroon and Nigeria (Tchoundjeu et al. 2008). The work progressively expanded into Equatorial Guinea and Gabon in 2002, the Democratic Republic of Congo and Ghana in 2004.

Priority species for domestication have been jointly identified by researchers and farmers following a priority setting carried out in Cameroon, Gabon, Ghana and Nigeria (Franzel et al. 1996). There was considerable variability among farmers' priority species within and between the countries surveyed. However, three species ranked among the top four in at least two of the countries. All three were important as both food and cash earners. Ten underutilized indigenous fruit trees of Africa having food nutritional security, reported by Omotayo and Aremu (2020) have also been included among priority species explained below.

Irvingia gabonensis (bush mango) is a large evergreen tree belonging to the family Irvingiaceae. It is widely distributed in moist semi-deciduous forests in West and Central Africa. Its geographical distribution covers Angola, Cameroon, Central African Republic, Congo, Cote d'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Gabon, Ghana, Guinea-Bissau, Liberia, Nigeria, Senegal, Sierra Leone, Sudan and Uganda. This tree is prized for its large kernels, which are used as a condiment in soups known as 'ogbono' in Nigeria. In addition, the fruits of some varieties are eaten fresh. The kernel is also used in preparing sauces and cakes. The kernel is also used for medicinal purposes and as a source of oil for making soap (Ayuk et al. 1999a). This species is an important component of regional trade in West Africa. It is also a source of timber, poles and fodder. The bark is used in the treatment of various ailments such as hernia, yellow fever, dysentery, diarrhoea, and as an antidote for poisons. Farmers usually preserve this tree on farms as a shade tree for crops such as coffee and cocoa and to restore soil fertility (Ayuk et al. 1999a).

Dacryodes edulis (bush butter or prune, safou) belongs to the family Burseraceae. It is found in humid tropical climates with geographic distribution covering nearly all of the western coast of Africa across to Uganda (Ayuk et al. 1999b). It has been known to occur in Angola, Benin, Cameroon, Central African Republic, Congo, Cote d'Ivoire, Democratic Republic of Congo (DRC), Equatorial Guinea, Gabon, Ghana, Liberia, Nigeria, Sierra Leone, Togo and Uganda. It is now widely planted by farmers in Nigeria, Cameroon and DRC, and in association with coffee and cocoa in some countries (Schreckenberg et al. 2002). The fruit is eaten raw, boiled or roasted and is an important food during its brief fruiting season. The fruit pulp yields about 48% edible oil. The fruits have very high cash value because they are sold widely in most countries of Central Africa. The oil is used widely in cosmetic and food industries. The kernel can be used as fodder for sheep or goats. The tree is also a source of many herbal medicines including the treatment of yellow fever, diarrhoea and anaemia (Ayuk et al. 1999b). It has also long been used in the traditional medicine of some African countries to treat various ailments such as wound, skin diseases, dysentery and fever. Ajibesin (2011) provides a comprehensive review of the ethnomedicinal uses of products from this tree, its chemical constituents and the biological effects.

Chrysophyllum cainito (star apple) belongs to the family Sapotaceae. It is widely distributed in the tropical rain forest and coastal region of West Africa (Nigeria, Niger, Cameroon and Cote d'lvoire and East Africa (Uganda). The flesh fruit is eaten especially as snack and relished by children. The fruits are also processed into jams and jellies. The bark, foliage and fruits are also used in traditional medicines (Houessou et al. 2012). The African star apple is produced commercially in West Africa.

Garcinia kola (bitter kola) belongs to the family Clusiaceae. It is found in moist forests throughout West and Central Africa including Cameroon, Ghana, Nigeria and Sierra Leone. The species is one of the most important trees valued in West Africa. The seeds are widely traded in West Africa. Every part of the plant has some medicinal uses. The seeds have pharmacological uses in treating asthma, coughs, poisoning, vomiting, throat infections, bronchitis and hepatitis (Abu et al. 2013). Experimental studies have confirmed antibacterial, anti-hepatoxic, antioxidant, anti-inflammatory and hypoglycaemic properties of its extracts (Abu et al. 2013). The extracts from seed and dry powered seeds have been made into tablets, cream and tooth paste. *Gacinia kola* seeds are also used as dietary food supplement, as flavour enhancer in the beverage industry and also as hop substitute in several indigenous alcoholic drinks.

Garcinia livingstonei (Imbe), is also important and preferred tree of tropical African nations including Uganda, Swaziland, South Africa, Somalia, Angola and Congo. The fruits are harvested for local use. The powdered root is used as an aphrodisiac and the fruit is said to be fermented into a pleasant alcoholic beverage which could help in improving health (Omotayo and Aremu 2020).

Allanblackia floribunda, a tree belonging to the family Clusiaceae, is an oil tree producing unique vegetable oil that comes from the seeds in tropical Africa. Although fruits are still mostly wild harvested, but there is a potential international market for its oil. Oil from the seeds has been extracted for generations and used for cooking or soap making, but a new use has been found because its oil melts and solidifies at temperatures just right for making margarine – similar to palm oil but easier to process. However, *Allanblackia* tree is considered vulnerable on the IUCN Red List of Threatened Species.

Balanites aegyptiaca syn *B. roxburghii*, a small tree belonging to family Zygophyllaceae (commonly known as balanite or desert date), is prevalent in all African regions including Northern Eastern, Central and Southern Africa, and also the Sahel-Savannah region across Africa, especially in West African countries including Mali, Benin, Senegal, Nigeria and Burkina Faso. It can be found in many kinds of habitat, tolerating a wide variety of soil types, from sand to heavy clay; and climatic moisture levels, from arid to subhumid. It is relatively tolerant to biotic pressure including fire and regenerates quickly from root-stock (https://en.wikipedia.org/wiki/Balanites_aegyptiaca - cite_note-fao-7). It has been cultivated in Egypt for more than 4000 years and is a good agroforestry tree as it fixes nitrogen and the foliage is rich in nitrogen contents and being spiny in nature forms good fence. As stated earlier, it is a very useful during famine. Its desert date fruit, mixed into porridge is given to nursing mothers. Date used to treat worm infection and liver and spleen disorders (Omotayo and Aremu 2020). A bark decoction is used as an abortifacient. The seed contains 30–48% non-volatile oil and all parts contain saponins.

11.2.2 The Sahel Region

The Sahel region, a semi-arid area stretching from Niger to Senegal, is characterized by high temperatures throughout the year and unpredictable rainfall patterns. This region is characterized by parklands, the principal agricultural system where a mixture of trees and shrubs are managed by farmers together with staple food crops, such as millet and sorghum. A number of indigenous fruit trees and shrubs provide fruits, leafy vegetables, nuts, oil and condiments that complement staple food crops in the local diet. In a survey conducted across Senegal, Mali, Burkina Faso, and Niger, a total of 59 indigenous fruit tree species were identified (Franzel et al. 2008). Out of these priority species (Table 11.2) were identified through participatory approaches for domestication. These species were preferred by farmers because of their nutritional, medicinal and income-generating values (Kalinganire et al. 2008).

Adansonia digitata (common name: baobab), a member of the family Bombacaceae, is indigenous to Africa where it is found in many countries (Kamatou et al. 2011). It occurs widely across the Sahel in savannahs of Sub-Saharan Africa. It is an emblematic and culturally important tree. It is often referred to as 'arbre a palabre', meaning the place in the village where the elders meet to resolve problems. Its leaves, bark, fruit pulp, seed and roots are used for medicines. The sun-dried fruit pulp is eaten either raw or added to sauces. Juice, rich in vitamin C, is prepared from the fruit pulp. A fermented baobab seeds known as *Maari* is part of the local diet in Burkina Faso (Parkouda et al. 2012, 2015). The leaves are used as vegetable consumed with cereal-based meals. Seeds are also used in soups or roasted and consumed as snacks (Sidibé and Williams 2002). The plant parts are used to treat various ailments such as diarrhoea, malaria and microbial infections. Baobab has numerous biological properties including antimicrobial, antiviral, anti-oxidant and

Table 11.2 List of the four most preferred priority indigenous fruit tree species in selected regions (adapted from Akinnifesi et al. 2009a)

Region	Rank 1	Rank 2	Rank 3	Rank 4
West Africa (Cameroon, Ghana and Nigeria)	*Irvingia gabonensis* (Bush mango)	*Dacryodes edulis* (African plum)	*Chrysophyllum cainito* (star apple)	*Garcinia kola* (bitter kola)
Sahel (Burkina Faso, Mali, Niger and Senegal)	*Adansonia digitata* (baobab)	*Tamarindus indica* (tamarind)	*Vitellaria paradoxa* (shea)	*Ziziphus mauritiana* (ber)
East Africa (Ethiopia, Kenya, Sudan and Uganda)	*Adansonia digitata* (baobab)	*Tamarindus indica* (tamarind)	*Ziziphus mauritiana* (ber)	*Sclerocarya birrea* (marula)
Southern Africa (Malawi, Tanzania, Zambia and Zimbabwe)	*Uapaca kirkiana* (wild loquat)	*Strychnos cocculoides* (monkey orange)	*Parinari curatellifolia* (mabula)	*Ziziphus mauritiana* (ber)

anti-inflammatory activities amongst others (Kamatou et al. 2011). The global demand for baobab seed oil and fruit pulp by the food and beverage, nutraceutical and cosmetic industries has increased dramatically in recent years (Kamatou et al. 2011).

Detarium microcarpum (detar) is a small leguminous tree of family Fabaceae that occurs widely in the Sahel region including Senegal, Mali, Burkina Faso, Cameroon, Chad, Nigeria and Sudan. It also occurs in the drier areas of Benin, Cameroon, Central African Republic, Gambia, Ghana, Guinea, Nigeria and Togo. Its fruits are consumed raw or cooked, or processed into cakes. The pulp is used to make an alcoholic beverage and in the preparation of couscous (Kalinganire et al. 2008). Seeds are dried, ground and used as fragrance. Mosquito repellent is prepared from the roots, while medicines are prepared from the seeds, fruits, leaves, roots and bark.

Parkia biglobosa (Néré) is a deciduous leguminous tree (family Mimosaceae) that occurs naturally across 15 countries in West Africa, parts of central Africa (Central African Republic and Republic of Congo) and parts of East Africa (Ethiopia, Sudan and Uganda) (Hall et al. 1997). It is the dominant species in the parklands, and it is managed in association with groundnuts, maize, millet and leafy vegetables (Bayala et al. 2002). As a legume, its seed are rich in protein, lipids, carbohydrates and minerals while the fruit pulp is high in carbohydrates and Vitamin C. The fresh fruit pulp is fermented into a beverage. In addition, the flowers are consumed. Its seeds are ground into a spice or condiment locally called 'soumbala', which is an important source of protein that is added to soups and stews throughout the Sahel. The species is considered as a commodity of local and regional trade in sub-Saharan Africa, especially in Benin, Burkina Faso, Cote d'Ivoire, Mali and Nigeria and is also a valuable source of fodder. Its branches are usually lopped by farmers and fed to livestock, especially in the dry season when good quality feed is scarce.

Tamarindus indica (tamarind) is a leguminous species (Family Fabaceae) indigenous to Africa. It probably originated in East Africa, but now naturalized in many countries in the Sahel and West Africa and the Indian sub-continent. Farmers commonly cultivate it in parklands in the arid and semi-arid zones of West Africa. In the Sahel, the fruit pulp is used primarily for sauces, porridge and juice. In Kenya, the fruit pulp is also used to tenderize meat, but this practice is unknown in the Sahel. Tamarind can be used as snacks, sauces, confectionery, drinks, jam, ice cream, wine, coffee-substitute, pectin, food stabilizer, dye, animal fodder, glue, edible oil and medicine. Tamarind is also a valuable timber species used in making furniture, tool handles, charcoal, and fuel wood. In addition, the leaves, flowers, root, bark, fruit pulp and seeds are an important source of herbal medicines (Bhadoriya et al. 2011).

Vitellaria paradoxa (Karité) is an indigenous African species belongs to the family Sapotaceae. It is abundant across the savanna between the equatorial rain forest and the Sahel. Its natural range extends from eastern Senegal to the high plateau of Uganda. There are two sub-species of *V. paradoxa* subspecies *paradoxa*, which occurs in the Sahel, produces a solid fat or butter while the Eastern Africa subspecies *nilotica* produces a liquid oil, which contains most of the therapeutic substances found in shea-butter. Nilotica shea-butter is softer and more fragrant than West African shea-butter. The fruits are not eaten fresh, but seeds are used as nutritious food condiment. The tree's main product is the shea butter extracted from the nuts. In addition to local uses, shea butter is exported for use in chocolate products and pharmaceuticals industries in European and other markets. Shea kernel is a very important export commodity and contributes significantly to the generation of revenues to many countries in the region. Annual exports to Europe are about 40–75,000 tons, with another 10–15,000 tons sold to Japan (Kalinganire et al. 2008). Mature fruits are eaten fresh and flowers are made into fritters.

Ziziphus mauritiana (ber) belongs to the family Rhamnaceae. Its origin is believed to be in Southeast Asia but it is naturalized in many parts of Africa. In the Sahel its main use is the fruit pulp, which is consumed fresh or dry, and also prepared into a juice. In addition, leaves are used for fodder, and the leaves, roots and bark are used for medicinal purposes. The wood is used for handles, kitchen utensils, firewood and charcoal. Among the selection criteria are plant vigour, early fruit set, sweet fruits, resistance to pests and disease, small seeds, big and round fruits, good fruit conservation, less thorns, high fruit, large canopy with many branches for greater fruit production. The tree can be propagated by budding and grafting techniques. Top grafting is the most popular technique for propagating this species in the Sahel.

11.2.3 East Africa

Dry lands cover 70% of the Eastern Africa region making it one of the driest in the world. Over 50 species of indigenous fruit trees occur in East Africa playing a crucial role in the diets of local people. The fruits of many of these species are important as a source of income during the late dry season and early wet season, when stocks of cereal crops usually are low (Teklehaimanot 2008). *Carissa edulis*, *Parinari curatellifolia*, *Sclerocarya birrea*, *Tamarindus indica* and *Ziziphus mauritania* were identified as national priority species for domestication (Jama et al. 2007; Teklehaimanot 2008). In a more recent priority setting conducted in Ethiopia, Kenya, Sudan, Tanzania and Uganda resulted eight priority indigenous tree species for domestication. These included *Adansonia digitata*, *Balanites aegyptiaca*, *Cordeauxia edulis, Sclerocarya birrea*, *Tamarindus indica, Vitelaria paradoxa*, *Vitex doniana* and *Ziziphus mauritania* (Teklehaimanot 2008). Recently, Omotayo and Aremu (2020) also included *Garcinia livingstonei, Strychnos spinosa, Uapaca kirkiana* and *Vangueria infausta* among priority species of East Africa.

Adansonia digitata (baobab) of family Bombacaceae occurs in semi-arid, deciduous savannahs in Ethiopia, Somalia, Eritrea, Sudan, Kenya, Tanzania, Central Africa Republic and Congo. The most important benefit of baobab is derived from its fruits. The fruits are used in porridges and as snacks particularly for children (Jama et al. 2007). Seeds are also eaten fresh, dried or roasted. Fresh and dried leaves, which are rich in vitamin A, are cooked and eaten as a vegetable (Teklehaimanot 2008). The pod contains a very nutritious pulp, which is rich in vitamin C (Table 11.3), calcium, potassium, phosphorous, iron and protein. The dry

Table 11.3 Nutritional composition of the fruit pulp of priority indigenous fruit trees of Africa

Species	Country	Energy (KJ 100 g^{-1})	Protein (%)	Fat (%)	Vitamin C (mg 100 g^{-1})	Vitamin A (μg)	Iron (mg 100 g^{-1})	References
Adansonia digitata	Malawi	1480	3.1	4.3	179.1	21	58	Saka et al. (2008)
	Kenya	1214	2.2	0.8	270	–	7.4	Jama et al. (2007)
	Botswana	–	1.3		141.3	–	0.1	Amarteifio and Mosase (2006)
Annona senegalensis	Namibia	329	1.7	1.5	18.2	–	0.7	Saka and Msonthi (1994), Keya et al. (2000)
Balanites aegyptiaca	Kenya	1151	5	0.1	35	–	–	Teklehaimanot (2008)
Berchemia bicolor	Namibia	305	–	3.5	50.3	–	2.2	Saka and Msonthi (1994), Keya et al. (2000)
Chrysophyllum cainito	Nigeria	–	9.8	15.0	–	–	1.3	Arotupin et al. (2016)
Cordeauxia edulis	Ethiopia	446	13.3	11.6	–	–	–	Teklehaimanot (2008)
Detarium microcarpum	Mali	–	4.9	–	3.2	–	–	Kalinganire et al. (2008)
Diospyros mespiliformis	Namibia	210	1.4	0.5	24.6	–	1.0	Saka and Msonthi (1994), Keya et al. (2000)
Garcinia livigstonii	Namibia	258	0.8	0.3	5.4	–	0.3	Saka and Msonthi (1994), Keya et al. (2000)
Parinari curatellifolia	Malawi	1517	3	1.5	10.4	357	1.0	Saka et al. (2008)
	Tanzania	–	0.7	0.7	60.7	–	–	Saka et al. (2008)
	Namibia	533	1.6	0.5	70.9	–	0.9	Saka and Msonthi (1994), Keya et al. (2000)
Schinziophyton routanerii	Namibia	1410	7.8	0.5	27.0	–	2.5	Saka and Msonthi (1994), Keya et al. (2000)
Sclerocarya birrea	Malawi	–	–	–	–	35	1.7	Saka et al. (2008)
	Kenya	–	4.7	–	160.8	–	21.8	Saka et al. (2008)

	Kenya	225	3.6	0.5	194	–	–	Teklehaimanot (2008)
	Botswana		3.7	–	128.3	–	0.07	Amarteifio and Mosase (2006)
	Namibia	225	1.5	1.0	194	–	0.5	Saka and Msonthi (1994), Keya et al. (2000)
Strychnos cocculoides	Malawi	1390	11.5	6	22.9	22	60	Saka et al. (2008)
	Tanzania	–	0.47		46.2	–	–	Saka et al. (2008)
	Botswana	–	3.8	4.7	38.0	–	–	Saka and Msonthi (1994), Keya et al. (2000)
	Namibia	308	0.7	0.1	6.7	–	0.2	Saka and Msonthi (1994), Keya et al. (2000)
Tamarindus indica	Kenya	1490	4.1	1.6	9	–	–	Teklehaimanot (2008)
	Kenya	285	2	0.2	8	–	–	Jama et al. (2007)
Uapaca kirkiana	Malawi	1897	17	22.9	16.8	–	43	Saka et al. (2008)
	Tanzania	–	–	6.03	98.7	–	–	Saka et al. (2008)
Vangueria infausta	Malawi	1456	1.8	1.1	16.8	–	451	Saka et al. (2008)
	Tanzania	–	0.01	5.19	93.7	–	–	Saka et al. (2008)
	Botswana		3.0	–	67.7	–	0.09	Amarteifio and Mosase (2006)
	Namibia	498	1.4	4.3	4.7	–	1.1	Saka and Msonthi (1994), Keya et al. (2000)
Vitellaria paradoxa	Kenya	393	4.13	–	–	–	–	Teklehaimanot (2008)
Vitex doniana	Malawi	1445	5.7	2.6	19.6	175	285	Saka et al. (2008)
	Tanzania	–	0.26	0	98.7	–	–	Saka et al. (2008)
	Kenya	1459	2.6	29.6	1000	–	–	Teklehaimanot (2008)
Vitex mombassea	Tanzania	–	0.03	18.8	111	–	–	Saka et al. (2008)
Ximenia americana	Namibia	556	2.8	0.8	69.7	–	1.3	Saka and Msonthi (1994), Keya et al. (2000)

(continued)

Table 11.3 (continued)

Species	Country	Energy (KJ 100 g^{-1})	Protein (%)	Fat (%)	Vitamin C (mg 100 g^{-1})	Vitamin A (μg)	Iron (mg 100 g^{-1})	References
Ximenia caffa	Namibia	374	1.9	1.5	68.2	–	0.5	Saka and Msonthi (1994), Keya et al. (2000)
Ziziphus mauritiana	Malawi	1588	4.1	9.5	13.6	35	–	Saka et al. (2008)
	Namibia	1198	3.2	0.6	–	–	0.7	Saka and Msonthi (1994), Keya et al. (2000)
Ziziphus mucronata	Namibia	659	3.8	0.5	42.6	–	1.0	Saka and Msonthi (1994), Keya et al. (2000)

pulp is mixed with water to produce beverages. Coloured pulp is sold as sweet in many kiosks and supermarkets in Eastern Africa (Teklehaimanot 2008). Oil extracted from the seeds is often used for cooking. Bath oil, lotions and creams have also been developed from the oil for the cosmetic industries.

Balanites aegyptiaca, an indigenous African species as described earlier, has edible pulp and a hard woody endocarp enclosing an edible oil-rich seed (Table 11.3). Its young leaves are edible. The seeds are also rich in protein and energy. Local communities in drylands of Eastern Africa heavily rely on this resource as emergency food and are regular rural market commodities. Oil is extracted from the kernels are used for cooking and medicine. Commercially, *B. aegyptiaca* is a potential source of ingredients for the manufacture of cortisone and corticosteroid drugs (Teklehaimanot 2008).

Carissa edulis (simple spined num num), a small tree of family Apocynaceae is found distributed from Senegal to West Cameroons. Fruits and roots are consumed. These are used in sauces, condiments and spices as flavouring agents. Traditionally decoctions of roots are used as pain killer, chest complaints, in arthritis, rheumatism and to treat malaria. Root is useful in treatment of a variety of diseases including sickle cell anaemia, toothache, ulcer, worm infestation, epilepsy, and inflammation The fruits help in the treatment of dysentery. Various alkaloids such as saponin, flavonoids, tannins, anthraquinones and cardiac glycosides have been reported from root and fruit (Teke and Kuete 2014).

Cordeauxia edulis (yehib) is an indigenous leguminous shrub of family Fabaceae, mainly found in Ethiopia and Somalia. It produces a tasty edible nut of high nutritional and economic value. The nuts are rich in fatty acids and eaten fresh, dried, roasted or cooked. The nuts are sold on local markets in Ethiopia and Somalia. Leaves are infused as tea. Leaves also contain a brilliant red dye, cordeauxiaquinone that stains the hands and is used in dyeing of fabrics. Cordeauxiaquinone is also used medicinally to stimulate hemoponsis. The plant has attracted considerable interest as a potential food crop for arid areas (Teklehaimanot 2008). However, it is listed as one of the most threatened tree species by IUCN (1998).

Sclerocarya birrea (marula) is an indigenous African species belonging to the family Anacardiaceae, widely distributed across the Sub-Saharan Africa stretching from Senegal to Ethiopia in the north, southward to Natal in South Africa, and eastward to Namibia, Angola and southern Democratic Republic of Congo. Three subspecies of *S. birrea* are recognized: *S. birrea* subsp. *caffra*, *Sclerocarya birrea* subsp. *multifoliolata* and *Sclerocarya birrea* subsp. *birrea.* While *S. birrea* subsp. *multifoliolata* occurs in Tanzania, *S. birrea* subsp. *birrea* occurs through West, Northeast and East tropical Africa. *S. birrea* subsp. c*affra* is the most ubiquitous and occurs in East tropical Africa (Kenya, Tanzania), southern Africa (Angola, Botswana, Malawi, Mozambique, Namibia, South Africa, Swaziland Zambia and Zimbabwe). Kenya and Tanzania have higher genetic diversity of *Sclerocarya birrea* than other countries in the region. This species plays a very significant role in the diet and culture of people in many countries where it occurs. The fruit pulp is eaten fresh, boiled to a thick black consistency for sweetening porridge or fermented to make alcoholic drinks of both local and commercial value (Jama et al. 2007). The fruit is also used to make juice, jam, jellies and as a cosmetic agent. The kernels yield highly stable oil useful for cooking and manufacturing cosmetics. Butter is also extracted from the kernels, which is used for the production of cosmetics by cosmetic industries in Europe and USA (Teklehaimanot 2008). The leaves and bark have medicinal properties (Jama et al. 2007). The fruit *S. birrea* makes high value liquor, 'Amarula' in South Africa and is marketed worldwide.

Tamarindas indica (tamarind) is thought to have originated from Eastern Africa, from where it spread to Asia and Central and South America. The edible pulp is consumed fresh and used to make syrup, juice concentrates and exotic food specialities like chutney, curries, pickles and meat sauces. The fruit pulp contains high amount of vitamin C and sugar and is a much-valued food ingredient in many Asian and Latin American recipes. The seed is also a good source of protein and oil.

Vitellaria paradoxa (shea tree) of family Sapotaceae has been identified as a priority in Ethiopia, Sudan and Uganda. Both fruits and seeds of *V. paradoxa* are edible. The fruit is consumed fresh and sold on local markets. The oil is primarily used as a source of cooking fat. Shea butter is used by chocolate and cosmetic manufacturing industries worldwide. In Eastern Africa, shea has become an export commodity to a very small extent only in Uganda since 1990. However, the shea butter in Sudan and Ethiopia has never had access to the export market and still remains a source of household cooking fat by local communities (Teklehaimanot 2008).

Vitex doniana (African olive or Black Plum) belongs to family Lamiaceae. The ripe fruit of this species is edible and extensively traded locally. The oil extracted from the dried seeds of *V. doniana* is used for skin cream, resin and paint production. The leaves provide cattle feed, while other parts of the tree are used in traditional medicines (Teklehaimanot 2008).

Ziziphus mauritania (Ber or Jujube) of family Rhamnaceae produces fruits with high sugar content and a high level of vitamin C, phosphorus and calcium. The fresh fruits are mostly liked by children and eaten raw. Dried fruits are sold on local markets in Kenya and Sudan (Teklehaimanot 2008). The fruits are also boiled with rice and millet and stewed or baked or made into jellies, jams, chutneys or pickles (Jama et al. 2007). Oil is also extracted from its seeds.

11.2.4 Southern Africa

Indigenous fruit tree species are important sources of vital nutrients and income to rural households in southern Africa (Akinnifesi et al. 2008a, b). Several studies have confirmed that wild fruits from the miombo woodlands are the major sources of coping with seasonal food shortages in Zimbabwe, Zambia, Malawi, Mozambique and Tanzania (Akinnifesi et al. 2008a, b, c, d; Dagar et al. 2020). Although over 60 species of indigenous fruit trees have been cited from southern Africa, the following are among the top most ranked for research and development in southern Africa (Table 11.2):

Uapaca kirkiana (sugar plum, masuku or mahobohobo) is a member of the family Phyllanthaceae. This species occurs naturally in southern, central and eastern Africa including Angola, Democratic Republic of Congo (DRC), Burundi, Tanzania, Malawi, Mozambique, Zambia and Zimbabwe. Extensive pure stands are often found on sandy or gravely soils with good drainage (Chirwa and Akinnifesi 2008) but with low exchangeable cations, organic matter and nutrients. Traditionally wood is used for carpentry and charcoal making. Fruit is a delicacy and consumed raw. The fruit juice is mixed with sorghum meal to form a thin, orange-flavoured porridge. Root infusion is used to treat indigestion and dysentery. The leaves are used as repellent to cockroaches. The bark is used as medicine against dysentery and indigestion. Leaves are used as fodder for cattle and help against dysentery and intestinal-related problems (Omotayo and Aremu 2020).

Some of its products have become commercialized at local, regional and international levels. Examples of commercial alcoholic beverages from *U. kirkiana* fruits include wine and Chikoto beer. The fruits are set between January and February, and mature in August and November. Another notable importance of *U. kirkiana* is its association with ectomycorrhizal fungi that form mushrooms, some of which have a significant impact on the livelihoods of communities where it occurs. Sileshi et al. (2007, 2008) have reported the impact of fertilizer application and pest management in this commercial species. Amanita, *Cantharellus, Lactarius* and *Russula* constitute the most common genera of fungi which typically form ectomycorrhizae. It also hosts the edible bug *Encosternum delegoruri* in Malawi and Zimbabwe.

Strychnos cocculoides (monkey orange) belongs to the family Loganiaceae and widely occurs in Central and Southern Africa (Chirwa and Akinnifesi 2008). The fruit is rich in sugars, essential vitamins, minerals, oils and proteins. The ripe fruit is eaten fresh or is used to prepare a non-alcoholic drink (Saka et al. 2008). The seeds contain strychnine, which is a toxic substance. The fruit is used to make a dye that provides protection from insects and for colouring trays and containers. The roots are chewed to treat eczema while its decoction is used as a cure for gonorrhoea by local communities. The fruit is used in making eardrops, and a fruit preparation is mixed with honey or sugar to treat coughs. Ground leaves are used to treat sores and when soaked in water, the drained liquid is used as a spray for vegetables to repel insects such as aphids and scales. The wood is suitable for construction, making tool handles and building materials.

Strychnos spinosa (natal orange) is widely distributed in tropical and subtropical Africa in almost all regions bearing sweet-sour fruits consumed raw when ripe and making juice, jelly and beverages. The plant is used for snakebites, venereal disease, increasing the flow of breastmilk in lactating mothers, and enhancing physical strength. The roots are prepared as tea and use against cold symptoms, cough, gonorrhoea, and malaria (Omotayo and Aremu 2020).

Parinari curatellifolia (Mbola plum), a member of the family Chrysobalanaceae, is a large evergreen tree indigenous to Africa. Its known distribution covers 37 countries across Africa. In southern Africa it occurs in woodland and wooded grasslands. It produces edible fruit with 88% carbohydrates and rich in vitamin C. The fruit may be eaten raw or made into a porridge. It is also made into a refreshing non-alcoholic drink. The oil-rich seeds (with 38% oil content) are pounded and used for making soup. In addition, it is a source of charcoal, timber and medicinal products.

Vangueria infausta (wild medlar) of family Rubiaceae is widely distributed in tropical Africa including Uganda, Kenya, Tanzania, Malawi, Mozambique, Zimbabwe, Namibia, Botswana, Swaziland and South Africa. The fruit is relished when ripe, used in puddings and even stored dry and the roasted seeds are consumed. Traditionally, it is used against gastro-intestinal disorders, malaria, pneumonia, cough, menstrual problems, parasitic worms, chest complaints, snake bites, infertility, fever, candidiasis and abdominal pains.

Ziziphus mauritiana (*Jujube*) as described above under Sahel and East Africa. It has been among the top preferred indigenous fruits widely consumed and traded fruit in southern Africa (Akinnifesi et al. 2006).

Ziziphus mucronata (buffalo thorn) is a small to medium size tree native of southern Africa. The ripen fruits are deep brown to red colour and are eaten when ripe and are found from February to August. The leaves are good fodder. The flowers bloom from October to April and attract honey bees. The leaves are edible and can be cooked as vegetable. The seeds can be roasted and ground as a substitute for coffee and the fruit are used to prepare a type of local beer (*ombike*). The wood is used for making implements and also as fuelwood. The leaves bark and roots are used medicinally for respiratory complaints and skin infections, and chest and stomach disorders. In east Africa, roots are said to be used for treating snake bites.

11.3 Nutritional Value

Recent analyses involving more than 3000 indigenous African species show their fruits are generally more nutritious than their exotic counterparts (Cernansky 2014; Akinnifesi 2017). Fruits and nuts from indigenous trees are a good source of energy, carbohydrates, protein, fats, vitamins and minerals (Table 11.3; Stadlmayr et al. 2013). The health benefits of fruits are also mediated through their antioxidant capacity (Vertuani et al. 2002). Proximate analysis (i.e. analysis of nutrients in which the gross components such as carbohydrate, proteins, fat, etc.) of fruits and seeds have been done for some species. However, fruits were mainly analysed for macronutrients and minerals and vitamins, mostly vitamin C (Stadlmayr et al. 2013). The lack of uniformity in methodology and incomplete reporting makes comparison of results across studies very difficult. In this section, we will focus on analysis of carbohydrate, proteins, fat and vitamin contents of fruits, nuts and seeds of the priority species. Since substantial compositional differences exist within a species, we provide information per country for priority species. For more detailed information, we refer the reader to Stadlmayr et al. (2013), who provide a general review of the literature.

11.3.1 Carbohydrate Content

Many fresh fruits are important sources of carbohydrates. Across a range of studies, the average carbohydrate contents were 74.9 g 100 g^{-1}in *Adansonia digitata* fruit pulp, in *Balanites aegyptiaca* dried fruit, 60.4 g 100 g^{-1}in *Tamarindus indica* fruit pulp, 28.7 g 100 g^{-1}in *Uapaca kirkiana* 68.8 g 100 g^{-1} fruit (Stadlmayr et al. 2013). On the other hand, *Ziziphus mauritiana* fruit pulp had very low carbohydrate content (8.3 g 100 g^{-1}). Nuts and seeds are also sources of carbohydrates. For example, seeds of *Irvingia gabonensis* contain 24–26% carbohydrate and the energy content is 641.1 KJ 100 g^{-1}; of *Cordeauxia edulis* carbohydrate 63.9%, energy 1666 KJ (Ejiofor et al. 1987; Adeniyi et al. 2014). *Chrysophyllum cainito* fruits contain 26–30% carbohydrate (Amusa et al. 2003; Arotupin et al. 2016). Besides these, Keya et al. (2000) while reporting chemical composition of veld fruits and vegetables, reported 86.8% carbohydrate in pulp of *Berchemia bicolor*, 81.7% in *Sclerocarya birrea*, 75.0% in fruit of *Schinziophyton rautanerii,* 25.0% in fruit (79% in peel) of *Vangueria infausta,* 28.9% in fruit of *Parinari curratellifolia,* 28.5% in *Ximenia americana* (energy 556 KJ 100 g^{-1}), 60.9% in fruit of *Z. maurtiana* (energy 1198), 34.4% in fruit of *Z. mucronata* (energy 659), 68.8% in flesh plus peel of *Grewia retinervis* (energy 1250), 42.1% in flesh plus peel of *G. avellena* (energy 851) and 67.0% in flesh plus peel of *G. bicolor* (energy 1302). The seeds of *Cordeauxia edulis* are also rich in fatty acids. Different parts of the fruit (peel, pulp, cortex, mesocarp, endocarp, etc.) contain different amount of carbohydrate and other mineral contents as reviewed by Dagar et al. (2020).

11.3.2 Protein Content

The protein content of the fruit pulp is highly variable, but the values reported for many species (Table 11.3) are higher than for commercial fruits such as orange (0.7 g 100 g^{-1}), mango (0.6 g 100 g^{-1}), grape (0.5 g 100 g^{-1}), banana (1.2 g 100 g^{-1}) and papaya (0.6 g 100 g^{-1}) (Rathore 2009). For example, *Chrysophyllum cainato* fruits with 8.8–9.8% protein (Amusa et al. 2003; Arotupin et al. 2016) contain 10 times more protein than those fruits. The seed of some species are rich in proteins. For example, *Irvingia gabonensis* seeds contain 7.4% protein (Ejiofor et al. 1987). The seeds of *Adansonia digitata* from Malawi, *Parinari curatellifolia* from Tanzania and *Sclerocarya birrea* from Kenya were reported to be 28.7%, 47%, and 33% protein, respectively (Saka et al. 2008). Seeds of *Cordeauxia edulis* contain protein 10.8% protein. *Adansonia digitata* seeds contain high amount of essential amino acids such as lysine and tryptophan (Osman 2004). Since lysine is limited in many cereals, *Adansonia digitata* seed protein holds high potential for fortifying cereal dominant diets (Osman 2004).

11.3.3 Fat and Oil Content

Although the fat content of the fruits and seeds varies widely with species, it is generally comparable or much higher than most commercial fruits (Table 11.3). For example, *Dacryodes edulis* fruits are 48% fat, while *Chrysophyllum albidum* fruit pulp is 14–17% fat (Amusa et al. 2003; Arotupin et al. 2016). The seed kernels of *Adansonia digitata*, *Parinari curatelifolia* and *Sclerocarya birrea* have been reported to contain 20–75% fat, which is comparable to those of leguminous seeds such as soybean (12–40%) (Saka et al. 2008; Thiong'o et al. 2002). According to Ejiofor et al. (1987), seeds of *Irvingia gabonensis* contain 53% fat, while Adeniyi et al. (2014) reported 10% fat, which is lower than in soybean seeds.

11.3.4 Vitamins

Vitamin C (ascorbic acid) was the predominant vitamin reported for most indigenous fruits; other vitamins were rarely reported (Stadlmayr et al. 2013). Although there is considerable variation within and between species, indigenous fruits are rich in vitamins (Table 11.3). The vitamin C levels of the edible parts of some species are superior to those of exotic and domesticated fruits. *Adansonia digitata*, *Sclerocarya birrea* and *Irvingia gabonensis* are rich sources of vitamin C, as they contain more than 30% of the nutrient reference value of 60 mg vitamin C per 100 g food (Stadlmayr et al. 2013). The fruit pulp of *Adansonia digitata* represents the most important natural sources of vitamin C, while the leaves are characterized by thigh content of provitamin A (Vertuani et al. 2002). According to a number of studies (cited in Kamatou et al. 2011; Stadlmayr et al. 2013), the vitamin C contents of *Adansonia digitata* fruit pulp across Africa (126–509 mg per 100 g) are 3–5 times higher than the vitamin C content of oranges (50–70 mg per 100 g). The vitamin C content of *Sclerocarya birrea* fruit pulp (85–319 mg per 100 g) is 2–4 times higher than those reported for fresh oranges or orange juice (Saka et al. 2008). Leakey (1999) reported high vitamin C content in the Nigeria population (403 mg per 100 g) that was twice as much as that of the Botswana population. Thiong'o et al. (2002) also reported Vitamin C content of 90–300 mg per 100 g in Kenyan populations of *Sclerocarya birrea*. The vitamin C content of 49–65 mg per 100 g reported for *I. gabonensis* (Stadlmayr et al. 2013) is comparable with the vitamin C content of oranges. The daily adult requirement of vitamin C is 45–80 mg per 100 g which implies that only 50 g of the edible part of indigenous fruits is sufficient to supply the body requirement of the vitamin. It is argued that without this valuable contribution many children who are most vulnerable and the chief consumers would be affected by dietary deficiencies (Makombe 1993). The indigenous fruits could also be a good source for the malnourished and people living with HIV/AID in Africa. The Vitamin A levels varied from 21 μg per 100 g in *Adansonia digitata* to 337 μg per 100 g in *Parinari curatellofolia* (Table 11.3).

11.3.5 Minerals

The fruits and seeds of indigenous fruits are also good sources of minerals especially iron (Table 11.3), calcium, magnesium, phosphorus, potassium, sodium, zinc and copper. However, high variability in mineral contents exists among and within the species (Stadlmayr et al. 2013). Across several studies iron values were high in dried fruit of *Balanites aegyptiaca* (13.8 mg per 100 g), *Uapaca kirkiana* (11.8 mg per 100 g) compared to other species (Stadlmayr et al. 2013). The Recommended Daily Allowance (RDA) of iron for 7–10-year-old children is 23 mg. Consumption of 1 kg of some of the raw fruits per day will give the child the recommended level of iron intake (Lutham 1997). This is lower than for commercial fruits for which more than 10 kg are required to meet the RDA.

11.3.6 Antioxidants

Carotenoids, flavonoids and polyphenols are the main phytochemicals with antioxidant capacities in fruits. Antioxidant capacity was not reported for most species except for *Adansonia digitata, Irvingia gabonensis*, *Garcinia kola* and *Dacryodes edulis* (Stadlmayr et al. 2013; Terashima et al. 2002). *Adansonia digitata* has a particularly high anti-oxidant capacity mainly because of it is high vitamin C content which is equivalent to 6 orange per 100 gm. According to Vertuani et al. (2002) *Adansonia digitata* fruit pulp had higher antioxidant capacity than fresh fruit pulp of strawberries, kiwi fruit, oranges and apples. Indeed, the integrated antioxidant capacity of *Adansonia digitata* fruit pulp (11.1 m mol g^{-1}) was 10 times more than that of orange fruit pulp (0.3 m mol g^{-1}) on a fresh weight basis (Vertuani et al. 2002). *Garcinia kola* seed is believed to contain flavonoids, with antioxidant capacity (Terashima et al. 2002).

Research on the nutritional, anti-nutritional and medicinal values of indigenous fruits has been on-going. However, this is occurring in an uncoordinated manner. In most cases, the analyses and reports are incomplete. Authors often focused on analysis of one or a few nutrients, and as can be seen in Table 11.3, our knowledge of the nutritional values is limited.

11.4 Fruit Trees and Agricultural Income

11.4.1 Income Generation

As discussed above, fruits of many trees such as marula, bird plum (eembe), monkey oranges, baobab (*Adansonia digitata*) and *Kigelia africana* are sold in market or along road sides as such or by transforming these into juice or jam and cake. Dry fruits of bird plum are frequently available in small markets even offseason. Gwary et al. (2000) conducted a survey and found that in north-central region of Namibia, 82% of the respondents claimed to get cash income from selling indigenous fruits or their products. The sold products were *Strychnos cocculoides* (54% of all households), false mopane (*Guibourtia coleosperma*, 46%) and *kashipembe* (46%), manketti nuts (21%), *Strechnos pungens* (7%) and *Dialium engleranum* (7%). Kalaba et al. (2009), in their survey found that in Zambia fruits of *Uapaca kirkiana* are collected and sold in local market by 74% of respondents, and of *Anisophyllea boehmii* by 71% followed by fruits of *Strechnos cocculoides* by 50%, *Parinari curatellifolia* by 30% and rest by sailing the small quantity of other fruits. Results of many such surveys from other regions are also available indicating products from marula, bird plum, *Hyphaene petersiana, Ziziphus maurtiana, Z. mucronata*, and *Diospyros mespiliformis* showing the importance of the indigenous fruits in meeting the livelihood requirements. Besides cash income, there are so many socio-economic advantages of these trees as these are the source of fuel, timber, agricultural implements, refreshing drinks and medicine.

Some active research has been undertaken in manketti and *Ximenia* oil and potentials of *Adansonia digitata* and *Kigelia africana* oils have been explored. In Kavango region in North Namibia, manketti (*S. rautanenii*) and Devil's claw (*Harpagophytum zeyheri*) are sold in local markets and *kashipembe* (alcohol) is the most important use of the manketti nuts (Vincent 1998). The process of oil extraction from nuts has been perfected by local people. Many of these have gone for commercial purpose. Research efforts are needed to find commercial uses of species such as *Diospyros mespiliformis* and *Parinari curatellifolia* fruits, which are already consumed, stored and transformed in various products by the rural people. Barion et al. (2001) indicated that it is possible to use dried bird plum fruit for making commercially acceptable country-wine. For commercial exploration, the species must be domesticated at farm level so that the required product is available in sufficient quantity. Thus, it is clear that above-mentioned fruits are helping in income generation of the rural people and have commercial potential and need domestication.

Omotayo and Aremu (2020) while reviewing studies revealed that the trading of fruits collected from the wild is a profitable enterprise and fruit collection is an efficient labour allocation strategy and its returns to labour are considerably higher than that of crop production. For example, the collection of *Uapaca kirkiana* generated an average of $50 in Zimbabwe and $78 for *Sclerocarya birrea* in South Africa (Akinnifesi et al. 2007). Furthermore, studies in Malawi, Tanzania, and Zimbabwe found that the percentage of net profit of indigenous fruit products reached 28% with higher profits being obtained in locations that are close to the markets (Akinnifesi et al. 2007). In South Africa, communities collectively harvested about 2000 Mg of *Sclerocarya birrea* fruits and earned $180,000 annually, representing more than 10% of average household income in the communities (Ham 2005). In addition, the members of a popular southern African Natural Products Trade Association reported gross revenue of $629,500 from the sale of fruit tree products. The key fruit tree products were obtained from *Sclerocarya* *birrea* and *Adansonia digitata* that generated $126,420 and $44,120, respectively (Akinnifesi et al. 2007). Based on a recent market projection, the potential market of *A. digitata* was valued at $960 million. Thus, the availability of market near to product collection is must and moreover, there is need to domesticate the important fruit trees on the farm for getting better managed product rather than collection alone from the wild.

11.4.2 Trends in Commercialization

Despite the importance of indigenous fruits to African consumers, relatively little success has been made in commercialization of their products. Trade in indigenous fruits is poorly developed and lags far behind the trading of exotic fruits. Only a couple of indigenous fruit products have made it onto the international market. 'Amarula Cream', made from the fruits of *Sclerocarya birrea* by the Distell Corporation in South Africa is probably one of the best-known examples (Ham et al. 2008). The Amarula Cream is sold in 63 countries and it is presently the second best-selling cream liquor in the world (Akinnifesi et al. 2006).

Another good example of successful commercialization is the seed oil of *Allanblackia floribunda*. The seed of this species yields oil widely used by local people in Tanzania. The oil was produced at commercial scale between 1972 and 1984 with involvement of local state-owned and community-led organizations in Tanzania (Mpanda et al. 2014). After a collapse of production, the business was revived in 2004 due to renewed interest in international markets. An ambitious programme was initiated to select productive germplasm and develop technology for earlier production of newly planted trees linking East and West African production areas to a major global supply chain (Mpanda et al. 2014).

The commercialization of *Dacryodes edulis* in Central Africa is another example. The fruit is exported mainly to the USA, Europe and also other countries within the region. The total export of its fruit from Cameroon was estimated at 93,995 Mg in 2007/2008 (Anonymous 2010).

Adansonia digitata is being exported to European and US markets as natural product by PhytoTrade. According to Sanchez et al. (2010) it is becoming a billion-dollar industry for Africa and creating employment opportunities for over 2.5 million households.

11.5 Challenges

11.5.1 Post-harvest Losses

Unlike exotic fruits, which are normally harvested according to specified methods and harvesting time, indigenous fruits are often collected using crude methods such as by knocking the fruit down with sticks, throwing objects to dislodge fruit, shaking the stem or branches, climbing the trees, and picking fruit up from the ground following abscission. These methods often cause excessive bruising, thus reducing the shelf life, quality and market value of the fruits and also damage the tree (Kadzere et al. 2004; Kalaba et al. 2009). The indigenous fruits that are affected the most include marula, *Uapaca kirkiana* and *Anisophyllea boehmii* due to their delicate outer covering when the fruit is fully ripe. In an attempt to reduce post-harvest losses of fruit, the local people use baskets called *museke* to transport these fruits to market. The basket allows the air to circulate through thereby avoiding fruit rot. Some rural people prefer harvesting fruit that are not yet fully ripe. The main injuries that the fruits sustain are abrasion injuries, impact injuries and compression injuries. These considerable losses of fruits reduce the quantity and quality of fruit available for consumption and sale. Fruit collectors often collect fruits that have fallen to the ground after abscission, which would leave only a limited consumption period and increase the chances of mechanical damage during the transport process. Methods for post-harvest handling of indigenous fruits are also poorly developed. The fresh fruits that are being marketed in urban centres go through a long handling chain before reaching the final consumer. Crude harvesting, packaging and transport activities decrease the shelf life of indigenous fruits dramatically and lead to spoilage and waste. Thus, fruits are subjected to post-harvest losses, both in quantity and quality. Saka et al. (2004) reported that fresh fruit incur direct or indirect nutrient and general quality loss from the field to the consumer. In quantifying the degree of fruits lost, Hughes and Haq (2003) reported post-harvest losses of fruit to be between 40% and 60%. These losses are attributed to a lack of knowledge in fruit handling and marketing.

11.5.2 Challenges in Processing and Value Addition

As in most products in Africa, indigenous fruits are often traded as raw materials or semi-processed raw materials. There are many problems along the supply and processing chains of indigenous fruits, and commercialization activities are in their infancy. Commercial companies are also processing fruit products with limited success (Ham et al. 2008). The reasons for this include lack of machinery to undertake processing, lack of skills to undertake research and development on fruit processing, lack of skills to run processing facilities, lack of finance to establish processing facilities, high maintenance costs for spare parts that have to be imported, high unit costs of running small processing facilities (Ham et al. 2008). While commercially viable processing requires a reliable supply of raw materials, uniformity and reliable quality of products, the situation is less than ideal for most indigenous fruits. As a result, cottage industries have failed to thrive. A case in point is the Mulunguzi winery in Malawi, which at one time produced wine from *Syzygium owariense*, *Uapaca kirkiana* and *Tamarindus indica*. Enterprises that processed and exported *Ziziphus mauritiana* and *Sclerocarya birrea* were initiated in Zambia but collapsed partly due to irregular supply of raw materials (Akinnifesi et al. 2009a, b). Access to technologies that meet processing and market requirements is also limited in areas where most indigenous fruit. Local small-scale processors, the majority of which are women, face a variety of problems including lack of skills, access to information and credit. Commercial processors also experience problems related to government support and technology information.

11.5.3 Challenges in Marketing

The lack of capacity to market fresh produce among local producers and the loss in quality during storage and transportation to the final market is a major limitation. Farmers often have to wait for traders before harvesting, which presents a particular problem during peak production periods and results in losses throughout the market chains. The lack of uniformity in quality is also a serious constraint. A basket of fruits usually comes from many different trees and as a result, wholesalers do not pay a good price (Leakey et al. 2002). Product quality and consistency of quality are major factors in the successful marketing. For many small-scale producers, consumer requirements remain unknown. Fruit markets also lack the necessary infrastructure and support systems to function optimally.

11.5.4 Other Challenges

There are some other inherent challenges which include inadequate baseline data on biochemical and food-related nutritional properties of fruit of individual indigenous fruit tree in relation to agro-climatic distribution of these trees; indiscriminate and illegal logging; lack of knowledge about the economic importance of different products hence the level of acceptability and accessibility of indigenous fruits; lack of policies regarding preference of local species rather than exotics creating insidious domination and preference for the exotic fruit tree species; inadequate knowledge on effective harvesting and storage technique as well as processing facilities; inadequate research facilities, priorities and support to innovations; and lack of political will and policies regarding promotion of domestication of indigenous fruit trees, value addition, creation of storage facilities and handling of market issues in favour of poor farmers.

11.6 Biodiversity Conservation

11.6.1 Indigenous Fruit Tree Diversity

Agrobiodiversity is the foundation of African agriculture, providing food, nutrition, and health and livelihood needs. Of the 20,000 plant species producing edible products, only 0.5% have been domesticated as food crops, although potential to develop new crops through participatory tree domestication has been a subject of intensive research in the tropics (Leakey et al. 2017). Harnessing the diversity of indigenous fruit trees may contribute to improved Africa's diet, nutrition and health, while reducing genetic erosion and extinction (Akinnifesi 2017).

One notable characteristic of wild tree species is their enormous genetic variability. Information on phenotypic and genetic variation is a prerequisite for the domestication and improvement of indigenous fruit trees. However, this has been studied only in a handful of the priority species such as *Adansonia digitata* (De Smedt et al. 2011; Munthali et al. 2012) and *Uapaca kirkiana* (Mwase et al. 2006). Therefore, investment is need in research for many of the species.

11.6.2 Overexploitation, Loss of Habitat and Ethno-Ecological Knowledge

There is a growing concern that increased interest in commercialization of products from the wild might cause over-exploitation. For example, in eastern Zimbabwe, where baobab bark is harvested for craft purposes, the trees are in danger of destruction in the short term as a result of harvesting and trade arrangements (Dovie 2003). Overexploitation combined with lack of natural regeneration, droughts and land clearing for agriculture, mining and infrastructure pose threats to baobab tree populations (Sanchez et al. 2010). Wild populations and the genetic diversity of many other species (e.g. *Cordeauxia edulis*) are threatened by increased clearing of forest for farms. This stresses the need for conservation strategies for wild populations and the need for planting on farmland. In many areas other indigenous fruit trees are undergoing losses due to habitat alteration through monocrop agriculture and cutting of trees for construction, fuelwood and charcoal (Teklehaimanot 2008). Much of the knowledge on indigenous tree species also remains with the local people, while scientific information on their uses and products remains inadequate (Haq et al. 2008).

11.7 Research Needs

A key research need is in the area of tree ecology and management. Such information can inform decision on where to cultivate desired species of trees. It is important to determine suitability of sites using either experimentation or modelling for large scale plantations. For example, a recent modelling study by Sanchez et al. (2010) identified areas highly suitable for wider cultivation of *Adansonia digitata* in Africa. Such information is urgently needed for scaling up the cultivation of other priority species as tree crops. Significant information is also needed on tree spacing, training, pruning, pest and disease management as well as harvesting, post-harvest management and value addition.

Another priority area for research is product and enterprise development. The narrow production period of some indigenous fruit trees results in the simultaneous ripening of all fruits. This often causes a glut in the market and low prices, followed by relative scarcity and high prices. Processing of fresh fruits immediately after harvesting may reduce losses. There has been relatively little work on product development and market standards. Hence, new innovative research and development efforts are needed to bring about improvements in marketing and small-scale enterprises. Research on processing, value addition, quality assurance and certification of products are also necessary for product development.

A third priority area for research is tree-crop interactions involving indigenous fruit trees. The planting of indigenous fruit trees on farmland can improve the productivity and sustainability of agriculture because trees are capable of increasing water and nutrient use efficiency of the systems. However, information is scanty on the ecological functions of such trees. Many of the areas where indigenous trees are managed in areas that are normally characterized by poor soil fertility and aridity. As discussed in Sect. 11.2, the influence of trees on microclimate and soil fertility plays a crucial role in the production of associated crops in these drylands. This has been traditionally exploited by farmers to sustain crop production especially in the parklands. However, problems such as shading and competition for water and nutrients remain subjects of scientific research. Although most studies on tree–crop interactions have focused on tree-cereal combinations, the results demonstrate that trees have highly variable effects on yields of the associated crops. Their effect on grain yields of cereals was found to be variable (Bayala et al. 2014). Yields of leguminous crops such as cowpea, groundnut and pulses were less affected by trees. On the other hand, tuber yields of the root crops *(e.g., Colocasia esculenta*) were improved under trees compared to the treeless monoculture plot (Bayala et al. 2014).

Empirical studies (reported in Boffa 1999) and analyses indicate reduction in yields of cereal crops due to the competition between the trees and the annual crops (Bayala et al. 2008, 2012). For example, Boffa (1999) reported reduction in sorghum and millet yield under *Vitellaria paradoxa*. Similarly, analyses by Bayala et al. (2012) revealed reduction in cereal yields under *Adansonia digitata*. Competition for light, nutrients and water between the trees and the crops were found to be the most important factor in yield reduction. However, the yield losses from the cereal crops are compensated for by fruit yield. Although in the short-term crop yields may be reduced due to competition, in the long-term favourable soil conditions are provided by the indigenous fruit trees (Bayala et al. 2002). These tree–crop interactions have been a subject of research only under a few species such as *Adansonia digitata*, *Parkia biglobosa* in the Sahel (Bayala et al. 2012; Sanou et al. 2012). Planting dwarf trees or crown pruning may reduce the shading effect, and its role as a management tool for reducing competition has also been studied. For example, studies on the pruning of *Parkia biglobosa* and *Vitellaria paradoxa* in the Sahel (Bayala et al. 2002, 2008) show that totally pruned trees give higher millet yields than due to effects of large tree crowns on photosynthetically active radiation (PAR). In the short-term millet yield could be improved by crown pruning, but long-term effects may depend on the ability of the trees to maintain soil fertility and on how quickly the trees recover from pruning (Bayala et al. 2002). While crown pruning may reduce competition, this must be balanced by the species ability to recover and produce fruits. Generally, slow recovery of crown in pruned trees is the most desirable characteristic in order to avoid the negative effect of tree shade on adjacent crop (Bayala et al. 2008). However, our understanding of when and where crop–tree interactions lead to increases in soil fertility or result in yield reduction is still limited. Hence, researchers need to generate more information on the attributes of the species and the processes that are involved in making each of these practices beneficial or not. This may be achieved through a combination of experimentation and process modelling. Valuing the contribution of indigenous fruit trees to the national economy is also long overdue. This can help in redirecting investments in research and development.

Research efforts are also needed to develop desired clones through tissue culture. This becomes more important for trees such as marula (being unisexual) to ensure large number of female trees. Investments in research are needed for genetic improvements in fruit quality, productivity and other desired traits in most preferred and economically important fruit trees.

11.8 Policies and Incentives

Beyond the basic research, enabling conditions, such as governance, gender synergies, secured land tenures, investment, proper and cheap financial support, markets for agroforestry inputs and sales of the products. This requires appropriate policy initiatives supporting political, social, cultural, economic and ecological factors to address the livelihood security of the poor (Kuyah et al. 2020). The guidelines formulated by FAO (2013) provide good fodder for developing suitable agroforestry-related initiatives including related to fruit trees, which include creation of awareness of the benefits of agroforestry systems among all stakeholders at local and global level; resolving unfavourable regulations and legal restrictions related to harvesting and marketing the produce and developing mechanism for interactions among the farming community and other stake holders at national and global level; securing of the land – use policy and land tenure issues at local level; strengthening the agroforestry policies that take into account the role of trees in rural development; organization of intersectoral coordination for better policy coherence and synergies; develop protocols at national and global level to pay the farming community and other agroforestry-dependent stake holders to pay suitably for the environmental services rendered by the agroforestry systems; strengthening of farmers' access to markets for agroforestry products (including fruit juice, oil, medicines, dairy and poultry products) and ensuring suitable prices for agricultural commodities; ensuring gender empowerment encouraging women-folk in sharing agroforestry benefits; and engaging good governance of rural activities such as skill development, creation of self-help groups and mass tree plantations.

The agroforestry policy must recognize the potential of indigenous, traditional and improved agroforestry practices to reduce poverty, enhance productivity, while also making agricultural landscapes more resilient to the risks of climate change. The comprehensive policy must intend to address the increasing demand for timber, food, fuel, fodder, fertilizer (adopting fertilizer trees) and fibre, while at the same time creating employment opportunities and generating income. India has become first nation to develop National Agroforestry Policy in 2014, which envisages the development of a National Agroforestry Mission/Board with an initial investment of approximately USD 33 million, to coordinate agroforestry-related activities in the country and the policy document highlights the climate change mitigation and adaptation benefits of agroforestry and it is assumed that the agroforestry plan will help increase the area under agroforestry from 25 to 53 million ha (NAP 2014). The main strategies of implementation of the policy (which can successfully be implemented in other nations including in Africa with minor modifications) may include: (1) Establishment of institutional set up (such as AF Mission or Board formation) at national level to promote agroforestry; (2) establishment of simple regulatory mechanism for harvesting, transiting and marketing of AF produce; (3) developing sound data base and information system; (4) invention in research, extension and capacity building; (5) improving farmers' access to quality planting material; (6) providing institutional credit and insurance cover for adopting agroforestry; (7) facilitating increased participation of industries dealing with AF products, mainly in rural areas at the sites of production of a particular commodity and encouraging farmers' cooperative or self-help groups; (8) strengthening farmers' access to markets for AF products and ensuring to them the profitable prices for their produce; (9) incentives to farmers for adopting AF practices; (10) promoting sustainable AF for renewable biomass-based energy and (11) suitable payment of agroforestry services to those who adopt the agroforestry practices.

11.9 Conclusions and Prospects

Through the propagation and cultivation of indigenous fruit trees on farm, opportunities exist for developing indigenous fruit trees as horticultural crops and for wider commercialization of their products. Past research has identified priority species for

R & D in many parts of SSA. Appropriate domestication strategies and protocols for vegetative propagation have also been developed for some of the priority species. Very few cases of active promotion and successful commercialization have been documented in Africa. The challenge is to develop superior ideotypes for the market, which can be done through clonal propagation. This will require more strategic research tailored at consumer needs and preferences. More research is also needed to develop appropriate field management practices. Tree crops for the future that will emerge from the domestication of indigenous fruits should aim at meeting farmer needs and market demand; creating or expanding market opportunities through superior germplasms and products, and development of market ideotypes.

References

Abu AH, Amuta PO, Buba E, Inusa TR (2013) Evaluation of antispermatogenic effect of *Garcinia kola* seed extract in Albino rats. Asian Pac J Reprod 2:15–18

Adeniyi S, Adedotun A, Akinniyi O (2014) The effects of post harvest mycodeterioration on the proximate composition of Irvingia gabonensis seeds. Int J Phytopathol 3:41–48

Ajibesin KK (2011) *Dacryodes edulis* (G. Don) H.J. Lam: a review on its medicinal, phytochemical and economic properties. Res J Med Plants 5:32–42

Akinnifesi FK (2017) Domesticating indigenous agro-biodiversity for improved food and nutrition in Africa. Nat Faune 31:13–17

Akinnifesi FK, Kwesiga FR, Mhango J, Mkonda A, Chilanga T, Swai R (2004) Domesticating priority for miombo indigenous fruit trees as a promising livelihood option for small-holder farmers in Southern Africa. Acta Horticult 632:15–30

Akinnifesi FK, Kwesiga F, Mhango J, Chilanga T, Mkonda A, Kadu CAC, Kadzere I, Mithofer D, Saka JDK, Sileshi G, Ramadhani T, Dhliwayo P (2006) Towards the development of miombo fruit trees as commercial tree crops in southern Africa. For Trees Livelihoods 16:103–121

Akinnifesi FK, Ajayi OC, Sileshi G, Kadzere I, Akinnifesi AI (2007) Domesticating and commercializing indigenous fruit and nut tree crops for food security and income generation in Sub-Saharan Africa. Paper presented at the New Crops International Symposium, September 2007, Southampton, United Kingdom. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.456.5289&rep=rep1&type=pdf

Akinnifesi FK, Ajayi OC, Sileshi G, Matakala P, Kwesiga FR, Ham C, Kadzere I, Mhango J, Mng'omba SA, Chilanga T, Mkonda A (2008a) Creating opportunities for domesticating and commercializing miombo indigenous fruit trees in Southern Africa. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 137–170

Akinnifesi FA, Sileshi G, Ajayi OC, Tchoundjeu Z (2008b) Accelerating domestication and commercialization of indigenous fruit and nut trees to enhance better livelihoods in the tropics: lessons and way forward. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 393–428

Akinnifesi FK, Mhango J, Sileshi G, Chilanga T (2008c) Early growth and survival of three miombo woodland indigenous fruit tree species under fertilizer, manure and dry-season irrigation in southern Malawi. For Ecol Manag 255:546–557

Akinnifesi F, Sileshi G, Mkonda A, Mhango J (2008d) Germplasm collection, propagation and nursery management of indigenous fruits. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 342–369

Akinnifesi FK, Ajayi OC, Sileshi G (2009a) Domestication and commercialization of forest tree crops in the tropics. In: Sustainable land management sourcebook. The World Bank, Washington, DC, pp 60–64

Akinnifesi FK, Mng'omba SA, Sileshi G, Chilanga TG, Mhango J, Ajayi OC, Chakeredza S, Nyoka BI, Gondwe FMT (2009b) Propagule type affects growth and fruiting of *Uapaca kirkiana*, a priority indigenous fruit tree of southern Africa. Hort Sci 44:1662–1667

Amarteifio JO, Mosase MO (2006) The chemical composition of selected indigenous fruits of Botswana. J Appl Sci Environ Manag 10:43–47

Amusa NA, Ashaye OA, Oladapo MO (2003) Biodeterioration of the African star apple (*Chrysophylum albidum*) in storage and the effect on its food value. Afr J Biotechnol 2:56–59

Anonymous (2010) Annuaire des statistiques du secteur agricole campagne 2007et 2008. MINADER/DESA/AGR-STAT 16:1–98

Arotupin DJ, Awojobi KO, Owolabi TR, Eze C (2016) Microorganisms associated with African star apple (*Chrysophylum albidum*) and their hydrolases. Afr J Microbiol Res 10:225–230

Ayuk ET, Duguma B, Franzel S, Kengue J, Mollet M, Tiki-Manga T, Zenkeng P (1999a) Uses, management and economic potential of *Irvingia gabonensis* in the humid lowlands of Cameroon. For Ecol Manag 113:1–9

Ayuk ET, Duguma B, Franzel S, Kengue J, Mollet M, Tiki-Manga T, Zenkeng P (1999b) Uses, management, and economic potential of *Dacryodes edulis* (Burseraceae) in the humid lowlands of Cameroon. Econ Bot 53:292–301

Barion S, Keya EL, Ngwira TN (2001) Country-wise making from eembe fruit (*Berchemia discolor*) of Namibia. J Food Technol Afr 6(3):83–86

Bayala J, Teklehaimanot Z, Ouedraogo SJ (2002) Millet production under pruned tree crowns in a parkland system in Burkina Faso. Agrofor Syst 54:203–214

Bayala J, Balesdent J, Marol C, Zapata F, Teklehaimanot Z, Ouedraogo SJ (2006) Relative contribution of trees and crops to soil carbon content in a parkland system in Burkina Faso using variations in natural 13C abundance. Nutr Cycling Agroecosyst 76:193–201

Bayala J, Ouedraogo SJ, Teklehaimanot Z (2008) Rejuvenating indigenous trees in agroforestry parkland systems for better fruit production using crown pruning. Agrofor Syst 72:187–194

Bayala J, Sileshi GW, Coe R, Kalinganire A, Tchoundjeud Z, Sinclaire F, Garrity D (2012) Cereal yield response to conservation agriculture practices in drylands of West Africa: a quantitative synthesis. J Arid Environ 78:13–25

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouedraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Belsky AJ, Amundson RG, Duxbury JM, Riha SJ, Ali AR, Mwonga SM (1989) The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. J Appl Ecol 26:1005–1024

Bhadoriya SS, Ganeshpurkar A, Narwaria J, Rai G, Jain AP (2011) Tamarindus indica: extent of explored potential. Pharmacogn Rev 5(9):73–81

Boffa J-M (1999) Agroforestry parklands in Sub-Saharan Africa. FAO Conservation Guide 34, Food and Agricultural Organization of United Nations, Rome

Campbell BM (1987) The use of wild fruits in Zimbabwe. Econ Bot 41:375–385

Cernansky R (2014) Super vegetables: Long overlooked in parts of Africa, indigenous greens are now capturing attention for their nutritional and environmental benefits. Nature 522:146–148

Chirwa PW, Akinnifesi FK (2008) Ecology and biology of *Uapaca kirkina*, *Strychnos cocculoides* and *Sclerocarya birrea* in Southern Africa. In: Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utilisation and commercialisation. CABI International, London, pp 322–340

Dagar JC (2003) Domestication on post-harvest handling and marketing of selected indigenous fruit trees. Final Report FAO Project (TCP/NAM/0167). Food and Agric Org of UN, Windhoek

Dagar JC, Sileshi GW, Akinnifesi FK (2020) Agroforestry to enhance livelihood security in Africa: research trends and emerging challenges. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes—recent advances and emerging challenges, vol 1. Springer, Singapore, pp 71–134

De Smedt S, Alaerts K, Kouyate AM, Van Damme P, Potters G, Samson R (2011) Phenotypic variation of baobab (*Adansonia digitata* L.) fruit traits in Mali. Agrofor Syst 82:87–97

Dovie DBK (2003) Rural economy and livelihoods from the non-timber forest products trade. Compromising sustainability in southern Africa? Int J Sustain Dev World Ecol 10:247–262

Ejiofor MAN, Onwubuke SN, Okafor JC (1987) Developing improved methods of processing and utilization of kernels of *Irvingia gabonensis* (var. *gabonensis* and var. *excelsa*). Int Tree Crops J 4:283–290

FAO (2013) Advancing agroforestry on the policy agenda: a guide for decision makers. Working Paper No.1. Food and Agricultural Organization of United Nations, Rome, p 37

Franzel S, Jaenicke H, Janssen W (1996) Choosing the right trees: setting priorities for multipurpose tree improvement. International Service for National Agricultural Research (ISNAR), The Hague, p 87

Franzel S, Akinnifesi FK, Ham C (2008) Setting priorities among indigenous fruit tree species in Africa: examples from Southern, Eastern and Western Africa Regions. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 1–27

Grouzis M, Akpo LE (1997) Influence of tree cover on herbaceous above and below ground phytomass in the Sahelian zone of Senegal. J Arid Environ 35:285–296

Gwary MM, Mahareto T, Kimoro C (2000) Socio-economic survey of Okongo community-a base line study for the Okongo Community Forest Project. SA-DC FSTUCU-GTZ Project, Namibia

Hall JB, Thomlinson HF, Oni PI, Buchy M, Aebischer DP (1997) Parkia biglobosa. A monograph. Publication number 9. School of Agricultural and Forest Sciences, University of Wales, Bangor

Ham C (2005) Plant for food and drink. Southern African trade directory of indigenous natural products. In: Mander M, Mckensie M (eds) Commercial products from the Wild Group Stellenbosch, South Africa, pp 17–22

Ham C, Akinnifesi FK, Franzel S, Jordaan DPS, Hansmann C, Ajayi OC, de Kock C (2008) Opportunities for commercialization and enterprise development of indigenous fruits in southern Africa. In: Akinnefesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 254–272

Haq N, Bowe C, Dunsiger Z (2008) Challenges to stimulating the adoption and impact of indigenous fruit trees in tropical agriculture. In: Akinnefesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 50–69

Houessou LG, Lougbegnon TO, Gbesso FGH, Anagonou LES, Sinsin B (2012) Ethno-botanical study of the African star apple (*Chrysophyllum albidum* G. Don) in the Southern Benin (West Africa). J Ethnobiol Ethnomed 8:40

Hughes A, Haq N (2003) Promotion of indigenous fruit trees through improved processing and marketing in Asia. Int For Rev (Special Issue) 5(2):176–181

IUCN (1998) *Cordeauxia edulis*. The IUCN red list of threatened species 1998: e. T30386A9533467. https://doi.org/10.2305/IUCN.UK.1998.RLTS.T30386A9533467.en. Accessed 29 Aug 2017

Jama BA, Mohamed AM, Mulatya J, Njui AN (2007) Comparing the "Big Five": a framework for the sustainable management of indigenous fruit trees in the drylands of East and Central Africa. Ecol Indicat 8:170–179. https://doi.org/10.1016/j.ecolind.2006.11.009

Jamnadass RH, Dawson IK, Franzel S, Leakey RRB, Mithöfer D, Akinnifesi FK, Tchoundjeu Z (2011) Improving livelihoods and nutrition in sub-Saharan Africa through the promotion of indigenous and exotic fruit production in smallholders agroforestry systems: a review. Int For Rev 13:338–354

Jonsson K, Ong CK, Odongos JCW (1995) Influence of scattered néré and karité on microclimate, soil fertility and millet yield in Burkina Faso. Exp Agric 35:39–53

Kadzere I, Hove L, Gatsi T, Masarirambi MT, Tapfumaneyi L, Maforimbo E, Magumise I (2004) Current status of post-harvest handling and traditional processing of indigenous fruits in Zimbabwe. In: Rao MR, Kwesiga FR (eds) Agroforestry impacts on livelyhoods in southern Africa: putting research into practice. Proceedings of the regional agroforestry conference held on 20–24 May, 2002, Warmbaths, South Africa. World Agroforestry Centre (ICRAF), Nairobi, pp 353–363

Kalaba FK, Chirwa PW, Prozesky H (2009) The contribution of indigenous fruit trees in sustaining rural livelihoods and conservation of natural resources. J Hort For 1(1):1–6. http://www.academicjournals.org/jhf

Kalinganire A, Weber JC, Uwamariya A, Kone B (2008) Improving rural livelihoods through domestication of indigenous fruit trees in the parklands of the Sahel. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, p 186

Kamatou GPP, Vermaak I, Viljoen AM (2011) An updated review of *Adansonia digitata*: a commercially important African tree. S Afr J Bot 77:908–919

Keya EL, Bille PG, Ngwira T (2000) Chemical composition of some edible indigenous wild fruits and vegetables. In: Proc. Conf. National Agricultural Research (Sept. 24–28, 2000), Namibia

Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Kuntashula E, Dimobe K, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes—recent advances and emerging challenges, vol 1. Springer, Singapore, pp 135–167

Leakey RRB (1999) Potential for novel food products from agroforestry trees: a review. Food Chem 66:1–14

Leakey RRB, Akinnifesi FK (2008) Towards a domestication strategy for indigenous fruit trees: clonal propagation, selection and the conservation and use of genetic resources. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 28–49

Leakey RRB, Akinnifesi FK (2017) Towards a domestication strategy for indigenous fruit trees in the tropics. In: Leakey RRB (ed) Multifunctional agriculture: achieving sustainable development in Africa. Elsevier, Academic Press, pp 165–176

Leakey RRB, Atangana AR, Kengni E, Waruhiu AN, Usuro C, Anegbeh PO, Tchoundjeu Z (2002) Domestication of *Dacryodes edulis* in West and Central Africa: characterisation of genetic variation. For Trees Livelihoods 12:57–72

Leakey RRB, Schreckenberg K, Tchoundjeu Z (2003) The participatory domestication of West African indigenous fruits. International Forestry Review 5:338–347

Leakey RRB, Tchoundjeu Z, Schreckenberg K, Shackleton SE, Shackleton CM (2005) Agroforestry tree products (AFTPs): Targeting poverty reduction and enhanced livelihoods. Int J Agric Sustain 3:1–23

Leakey RRB, Weber JC, Page T, Cornelius JP, Akinnifesi FK, Roshetko JM, Tchoundjeu Z, Jamnadass R (2017) Tree domestication in agroforestry: progress in the second decade (2003–2012). In: Leakey RRB (ed) Multifunctional agriculture: achieving sustainable development in Africa. Elsevier, Academic Press, pp 139–154

Leger S (1997) The hidden gifts of nature: a description to today's use of plants in West Bushmanland (Namibia). Ded, German Development Service, Windhoek

Lutham MC (1997) Human nutrition in the developing world. FAO Food and Nutrition Series number 29, FAO Rome Italy, p 508

Maghembe JA, Simons AJ, Kwesiga F, Rarieya M (eds) (1998) Selecting indigenous trees for domestication in Southern ICRAF, Nairobi, Kenya, Africa. p 94

Makombe K (ed) (1993) Sharing the land: wildlife, people and development in Africa. IUCN, Harare, Washington, DC

Mpanda M, Munjuga M, Reyes T, Said A, Rutatina F, Kimaro A, van Noordwijk M (2014) Allanblackia, butterflies and cardamom: sustaining livelihoods alongside biodiversity conservation on the forest–agroforestry interface in the East Usambara Mountains, Tanzania. For Trees Livelihoods 23:127–142. https://doi.org/10.1080/14728028.2014.895215
Munthali CRY, Chirwa PW, Akinnifesi FK (2012) Phenotypic variation in fruit and seed morphology of Adansonia digitata L. (baobab) in five selected wild populations in Malawi. Agrofor Syst 85:279–290
Mwase WF, Bjornstad A, Ntupanyama YM, Kwapata MB, Bokosi JM (2006) Phenotypic variation in fruit, seed and seedling traits of nine *Uapaka kirkiana* provenances found in Malawi. South Afr For J 208:15–21
NAP (2014) National agroforestry policy. Department of Agricultural Cooperation, Ministry of Agriculture, Government of India, New Delhi, p 29
Omotayo AO, Aremu AO (2020) Underutilized African indigenous fruit trees and food-nutrition security: opportunities, challenges and prospects. Food Energy Secur 9:e220. https://doi.org/10.1002/fes3.220
Osman MA (2004) Chemical and nutrient analysis of baobab (*Adansonia digitata*) fruit and seed protein solubility. Plant Foods Hum Nutr 59:29–33
Palgrave KC (1983) Trees of southern Africa. Struik Publishers Ltd., Cape Town, p 959
Parkouda C, Sanou H, Tougiani A, Korbo A, Nielsen DS, Tano-Debrah K, Jensen J (2012) Variability of baobab (*Adansonia digitata*) fruits' physical characteristics and nutrients content in West African Sahel. Agrofor Syst 85:455–463
Parkouda C, Ba F, Ouattara L, Tano-Debrah K, Diawara B (2015) Biochemical changes associated with the fermentation of baobab seeds in Maari: an alkaline fermented seeds condiment from western Africa. J Ethnic Foods 2(2):58–63
Rathore M (2009) Nutrient content of important fruit trees from arid zone of Rajasthan. J Hortic For 1:103–108
Saka JDK, Msonthi JD (1994) Nutritional value of edible fruits of indigenous wild trees in Malawi. For Ecol Manag 64:245–248
Saka JDK, Swai R, Mkonda A, Schomburg A, Kwesiga F, Akinnifesi FK (2004) Processing and utilisation of indigenous fruits of the miombo in southern Africa. In: Rao MR, Kwesiga FR (eds) Agroforestry impacts on livelihoods in southern Africa: putting research into practice. Proceedings of the regional agroforestry conference held in Warmbaths, South Africa 20–24 May, 2002. World Agroforestry Centre (ICRAF), Nairobi, pp 343–352
Saka JDK, Kadzere I, Ndabikunze BK, Akinnifesi FK, Tiisekwa BPM (2008) Product development: nutritional value, processing and utilization of indigenous fruits from the miombo ecosystem. In: Akinnefesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 288–390
Sanchez AC, Osborne PE, Haq N (2010) Identifying the global potential for baobab tree cultivation using ecological niche modelling. Agrofor Syst 80:191–201
Sanou J, Bayala J, Teklehaimanot Z, Bazie P (2012) Effect of shading by baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) on yields of millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) in parkland systems in Burkina Faso, West Africa. Agrofor Syst 85: 431–441. https://doi.org/10.1007/s10457-011-9405-4
Schreckenberg K, Degrande A, Mbosso C, Boli Baboule Z, Boyd C, Enyong L, Kanmegne J, Ngong C (2002) The social and economic importance of *Dacryodes edulis* (G.Don) H.J. Lam in southern Cameroon. For Trees Livelihoods 12:15–40
Sidibé M, Williams JT (2002) *Baobab: Adansonia digitata*. International Center for Underutilised Crops, Southampton
Sileshi G, Akinnifesi FK, Ajayi OC, Mkonda A (2007) Effect of growth media and fertilizer application on biomass allocation and survival of *Uapaca kirkiana* Müell Arg seedlings. Sci Res Essays 2:408–415

Sileshi G, Barklund P, Meke G, Bandeira RR, Chilima C, Masuka A, Day R (2008) Pest management in high commercial value indigenous fruit trees in southern Africa. In: Akinnefesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 370–392

Simons AJ, Leakey RRB (2004) Tree domestication in tropical agroforestry. Agrofor Syst 61:167–181

Stadlmayr B, Charrondière UR, Eisenwagen S, Jamnadass R, Kehlenbeck K (2013) Nutrient composition of selected indigenous fruits from sub-Saharan Africa. Journal of Science Food and Agriculture 93:2627–2636

Takimoto A, Nair VD, Nair PKR (2009) Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. Agrofor Syst 76:11–25

Tchoundjeu Z, Atangana A, Asaah E, Tsobeng A, Facheux C, Foundjem D, Mbosso C, Degrande A, Sado T, Kanmegne J, Mbile P, Tabuna H, Anegbeh P, Useni M (2008) Domestication, utilization and marketing of indigenous fruit trees in West and Central Africa. In: Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics-domestication, utilization and commercialization. CAB International, Oxfordshire, pp 171–185

Teke GN, Kuete V (2014) acute and subacute toxicities of African medicinal plants. In: Kuete V (ed) toxicological survey of African medicinal plants. Elsevier, pp 63–98

Teklehaimanot Z (2008) The role of indigenous fruit trees in sustainable dryland agriculture in Eastern Africa. In: Akinnifesi FK, Leakey RB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: domestication, utillization and commercialization. CABI, Wallingford, pp 204–230

Terashima K, Takaya Y, Niwa M (2002) Powerful antioxidative agents based on garcinoic acid from *Garcinia kola*. Bioorg Med Chem 10:1619–1625

Thiong'o MK, Kingori S, Jaenicke H (2002) The taste of the wild: variation in the nutritional quality of Marula fruits and opportunities for domestication. Acta Hortic 25:237–244

Vertuani S, Braccioli E, Buzzoni V, Manfredini S (2002) Antioxidant capacity of *Adansonia digitata* fruit pulp and leaves. Acta Phytother 2:1–7

Vincent P (1998) Complementary data of NTFP uses and markets in the Kavango region. Report of Non-Timber Forest Products Project. CRIAA-SA-DC Namibia

Walker N (1989) King of foods. Marula economics in the matabos. Afr Wildl 43(6):281–285

Chapter 12
Ethnic Homestead Gardens: Diversity, Management and Conservation

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Abstract With the adoption of modern agricultural practices, concerns have grown about the long-term sustainability and environmental consequences of the intensification of agricultural systems. As such, traditional agroforestry systems can play a significant role in achieving nutritional and ecological security due to their multifunctional role. Homestead gardens (HGs) of the tropics, considered as one of the oldest forms of traditional land-use system, are regarded as the epitome of sustainability. They have long been seen as the most effective means for biodiversity conservation holding significant values in forest conservation and livelihoods. Despite the system's potential to provide sustenance to millions, they have received relatively little scientific attention. Hence, the objective of this chapter is to summarize the existing state of knowledge on HGs and their contribution to species diversity and conservation, as well as present a brief overview of some traditional management practices reported in the tropical and subtropical regions. The review revealed that plants species in the HGs vary from 9 to > 600 species with a density of ~342–4259 individuals ha^{-1} and Shannon–Wiener diversity index (H) of 1–4.9. Studies have shown that there is no standard size for HGs, but could range from ~0.003 to 2.4 ha or more with a mean size of ~0.42 ha in the tropics. Tropical HGs are known to show high floristic diversities compared with other agro-ecosystems with some reporting more diversity than nearby forests. The majority of the species are domesticated and managed by farmers for multiple uses and benefits where the most essential function is food production. Besides the tangible benefits, HGs provide multiple ecological functions including microclimate modifications and conservation of genetic resources, nutrient cycling and soil and water conservation. The traditional management practices under the tropical HGs are generally characterized by low input and use of very simple technologies. We argue for the

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recognition in development initiatives and formulation of appropriate policies for their conservation and better utilization of the genetic materials and indigenous knowledge associated with HGs.

Keywords Agroforestry systems · Biodiversity conservation · Multispecies systems · Species diversity · Sustainability · Traditional farming systems

12.1 Introduction

Throughout human civilization, one primary quest has been to produce food that sustains the needs of contemporary societies. With the advent of modern agricultural production technologies, many food-deficit nations have become self-sufficient and even food-surplus nations (FAO 2017). On the other hand, the majority of countries are still confronted with food shortages. This is further aggravated by climate change, increasing poverty and input prices. Hunger is a chronic problem, and based on the Global Hunger Index (GHI), 184 million people live in countries with hunger level rated *extremely alarming* or *alarming* (von Grebmer et al. 2021). Poverty, hunger and malnutrition work hand-in-hand in increasing the vulnerability of rural populations to climatic shocks. There is a growing concern whether current rates of food production can keep pace with the rapid population growth given the carrying capacity of land in most developing countries is already overstressed. Hence, modern agricultural technologies might not be the first and best option to improve smallholder farming systems in the tropics. Therefore, it will be more appropriate to use the natural processes and local resources to make farming more effective and create conditions for efficient, profitable and safe use of inputs in such regions (Reijntjes et al. 1992; Altieri 1995). In addition, the ecological sustainability and economic viability of modern technologies are also increasingly at stake.

Besides, some modern agriculture practices are also said to be unsustainable, mainly due to overemphasis on increasing production and achieving it through inappropriate manipulation (Smidt et al. 2016). Furthermore, modern agricultural practices are also reported unsuitable in forested areas (Kanianska 2016). Therefore, concerns have been rising on the long-term sustainability and environmental consequences of the intensification of agricultural systems. In this context, traditional agroforestry systems (AFS) can play an essential role in helping us achieve sustainable nutritional and ecological security (Das and Das 2005). Hence, traditional AFS are gradually gaining increasing attention from decision-makers, conservationists and the scientific communities due to their multifunctional role in sustainable development models for rural areas (Santoro et al. 2020).

Ethnic homestead gardens (HGs), also called 'homestead agroforestry'or simply 'home gardens' are typical traditional AFS that involves the integration of trees intercropped with shrubs and annual crops along with livestock, found in most tropical and subtropical regions (Nair 1993). According to Nair (1993), a traditional HG is a 'small-scale production system supplying plant and animal consumption and utilitarian items either not obtainable, affordable, or readily available through retail

Fig. 12.1 Vertical stratification of a typical homestead garden

markets, field cultivation, hunting, gathering, fishing, and wage-earning'. They occur immediately surrounding the home or further away, but near to residential areas (Soemarwoto 1987). HGs tend to be located close to dwellings for security, convenience and special attention and care. Many types of traditional HGs vary in their layouts and types of species grown and are associated with different geographical areas or ethnic groups. The deliberate arrangement of crops in both vertical and horizontal structure in the HGs has been observed as an ecologically sound practice (Shimrah et al. 2018). Niñez (1987) classified traditional HGs into two ecological types: tropical and temperate. Tropical HGs are known to have complex vertical structures with multiple species and life forms. They are composed of many woody and herbaceous species, carefully structured to form 3 to 5 vertical canopy strata, with each component having a specific place, as well as function (Fernandes and Nair 1986). On the contrary, temperate HGs have simple vertical structures with all the plants unshaded and dominated by annual species (Niñez 1987). Agroforestry, as an approach to land use is more relevant and has wider application in the tropics compared to the temperate zone and many land-use problems and constraints are readily addressed by these practices in the tropics (Nair 1993).

Studies have highlighted that there is no standard size for a HG system (Das and Datta 2018), and the size can vary depending on the socio-economic and ecological conditions. According to Fernandes and Nair (1986), the mean size for a HG unit varies from about 0.1 to 0.5 ha. The majority of the HGs are distributed in South and Southeast Asia, East and West Africa, Pacific Islands and Mesoamerica (Kumar and Nair 2004). A schematic representation of a typical traditional HG is provided in Fig. 12.1.

12.2 Typology and Micromanagement Zones of Ethnic Homestead Gardens

Micromanagement zones in HGs can be regarded as the horizontal stratification, are spatial areas deliberately allocated to particular species, as perceived by the HGs managers/farmers. Depending on site suitability, farmers identify and allocate resources into different zones (Méndez et al. 2001). Micro-zonation in HG is easily visualized and their location, size and plant species composition reflect deliberate management strategies. Plant species and their local uses, which are included in the zones, provide additional information on a farmer's management priorities and socioeconomic needs. To address the underlying causes of HGs design, management and selection of plant species is a promising technique to a better understanding of these land-use systems. These can be accomplished largely by studying the existing HGs micro-zonation (zones). Several studies have documented such management zones (Brierley 1985; Abdoellah 1990; Padoch and de Jong 1991; Das and Das 2005), but seldom used as a unit of analysis. As such, we stretch on the micro-zones (horizontal stratification) in the HGs presented by Méndez et al. (2001). Their study deliberately represented the different micro-zones present in HGs of Masaya, Nicaragua (Fig. 12.2), where as much as ten different management zones were identified and reported. According to their study, the total number of zones per HGs ranged between two and six, with a mode of three. All HGs were reported to have a minimum of two zones. They highlighted that with the increase in the HGs size, the percentage of the total area allocated to the residential zone area decreases. Therefore, the total area affected the number of zones only in smaller HGs.

In Masaya, Nicaragua, location of zones was deliberate in most HGs, farmers allot specific areas for zones, and their components based on factors like practical considerations, plant requirements and soil conditions. For example, herbaceous and ornamental plant species were in proximity to the residential area or households for constant watering and weeding, to safeguard against theft and to facilitate easy access for sale. Seedlings of certain food crops were generally allocated to areas of high soil fertility. Tree zones and shaded coffee were usually farthest from the residential area due to the comparatively lesser daily care or safeguard requirements. Zones of natural regeneration of multipurpose tree species (MPTs) were encouraged in cases suitable to the farmer. In common, most HGs area was allocated to fruit trees (37%) and residence (25%). Shaded coffee and ornamentals with shade trees were allocated 14–16% of the total HGs area and the average coverage of the remaining other zones was 3% or less. Kumar and Nair (2004) also mentioned that fruit- and food-producing plant species usually dominated near the households and working areas, while small plots of annual crops separate this part of the HGs from the more distant parts preferred for timber species. Ornamental and medicinal species are typically grown in small areas or in pots surrounding the house, and vegetables in areas adjacent to the kitchen. Hence, position or distance from residential zone, besides size, shape, crop composition and planting pattern of the HGs are the key determinants in this respect.

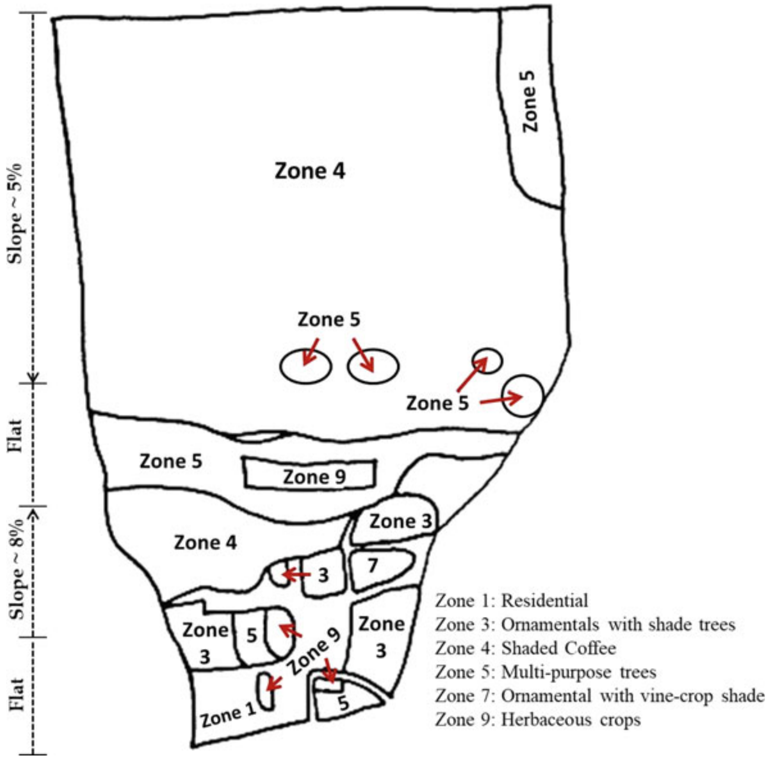

Fig. 12.2 Map of HG depicting plant components in six different management zones. (Adopted from Méndez et al. (2001))

In North-East India, the locations of most plants in HGs were deliberate, which could be distinguished into several management zones. Das and Das (2005) recorded five major management zones in HGs based on their function, location and composition: (1) bamboo groves (Bansh tilla), (2) betel groves (Gua baari), (3) banana groves (Kola baari), (4) vegetable garden (Sabje baari) and (5) dense or extended zones. The betel, banana and bamboo in HGs are so named as they are usually dominated by or composed of pure stands of betel, banana and bamboo. Singh et al. (2014) described structure and multiplicity in function, diversity and nutritional security to the family in the age-old traditional home gardens of Angami and Konyak Nagas of Nagaland; Meteis of Manipur; War Khasi of Meghalaya; Chuktuah Huan of Mizoram in North eastern India and found that most of these are rich in biodiversity consisting of local trees, fruit trees, vegetables, shade-tolerant spices and medicinal plants and are managed by family members primarily for their own use and occasionally for commercial purposes.

The Chagga home gardens in the foothills of Mount Kilimanjaro in Tanzania represent a typical example of ethnic homestead gardens (Fernandes et al. 1984; Hemp 2006). The Chagga began the process of transforming the native forest. They retained trees that provided fodder, fuel and fruit while eliminating less useful ones and replacing them with new tree and crop species. Chagga use four vegetation layers. Under a tree layer, which provides shade, fodder, medicines, firewood and construction wood, bananas are grown under the coffee trees, and under these vegetables (Hemp and Hemp 2008). This multi-layer system maximizes the use of limited land (Fernandes et al. 1984). The home gardens maintain not only a high biodiversity but also an age-old land use system that meets several different needs of the community.

12.3 Ethnic Homestead Gardens and Their Importance

In the tropical and subtropical regions, HGs form a chief component in the livelihoods and economy of the rural poor population (Kumar 2011; Roy et al. 2013), evolved in response to factors such as economic, cultural, environmental and also personal fondness as well (Southern 1994). The cropping patterns within the HGs depended on the owner choices, the availability of planting materials, farm size and farmers' financial capacity (Nair 1989). Nonetheless, farmers' interest circles primarily around the growing of MPTs, with particular preference to fruit tree species (Millet-E-Mustafa 1996). Hence, most of the plants domesticated, grown and managed under the HGs have multiple uses and play a significant role in providing nutritional and economic security. A study by Fernandes and Nair (1986) reported that the essential function of the HGs is food production. Other significant uses derived from the HGs include timber, fodder, medicine and fencing, thereby acting as a safety net by providing alternative livelihood sources to the farmers during crisis periods, including natural hazards (Kabir and Webb 2008).

Besides the tangible benefits, HGs also have many ecological merits related to microclimatic modifications and conservation of genetic resources, soil, water, nutrients, etc. (Masum et al. 2008; Singh et al. 2014; Nath et al. 2021). They are the site of highest plant diversity when compared with other cultivated fields (Coomes and Ban 2004) and are considered a key site for domesticating wild plants (Huai and Hamilton 2009). Studies have revealed that the plant species diversity under these traditional farming systems could potentially range from <5 to >100 (Roy et al. 2013). Due to the rich biodiversity conserved, HGs are also referred to as '*Biodiversity Island*' of a country (Alam and Furukawa 2010). Roy et al. (2013) presented a conceptual model of species diversity and biodiversity conservation under HG farming systems, presented in Fig. 12.3.

Structurally and functionally, HGs are the closest mimics of natural forests (Jose 2009). Due to its forest-like characteristics, it holds tremendous potential for climate change mitigation (Nath et al. 2021) and increases farmers' adaptive capacity (Nath et al. 2021; Reang et al. 2021a). HGs are also believed to have a higher potential to sequester carbon than pastures or field crops. HGs thus meet the conditions under the clean development mechanism project creating a win–win strategy for the farmers in climate change mitigation and adaptation initiatives and biodiversity conservation

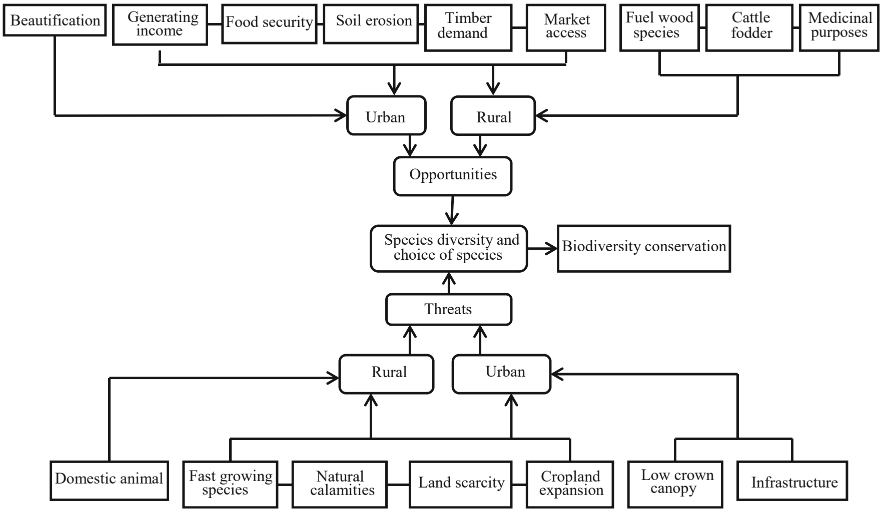

Fig. 12.3 A conceptual model of species diversity and biodiversity conservation under the HG farming system

(Nath et al. 2015). Therefore, these traditional land-use systems thus hugely support the implementation of REDD+ mechanism (reducing emissions from deforestation and forest degradation) (Reang et al. 2021a).

In addition, they are generally regarded to possess a closed nutrient cycling, much alike to the tropical forests (Nair et al. 1999) and also are characterized by low 'export' of nutrients. Besides, root systems of the multiple components are expected to overlap considerably and the resultant higher root-length density helps in reduced nutrient leaching thereby facilitating recycling of subsoil nutrients (Kumar and Nair 2004). Hence, HGs are perceived to be highly sustainable in both biophysical and socioeconomic terms. Given the above-highlighted importance, we aimed to present an overview of HGs and its potentials in relation to plant diversity, management systems and biodiversity conservation in the tropics through systematic literature synthesis and meta-analysis using the Web of Science platform. The total percentage of HGs articles used from the different tropical and subtropical regions in the present study and analyses is presented in Fig. 12.4.

12.4 Diversity in Ethnic Homestead Gardens

In HGs, plant density, species diversity and composition vary from place to place, influenced by ecological and socio-economic factors. Greater density and frequency of a plant species under HGs are considered as the most preferred species and indicates their level of active uses (Debbarma et al. 2015). Therefore, farmers' ethnic affiliation and origin have a major role in determining the inter-site dissimilarities in

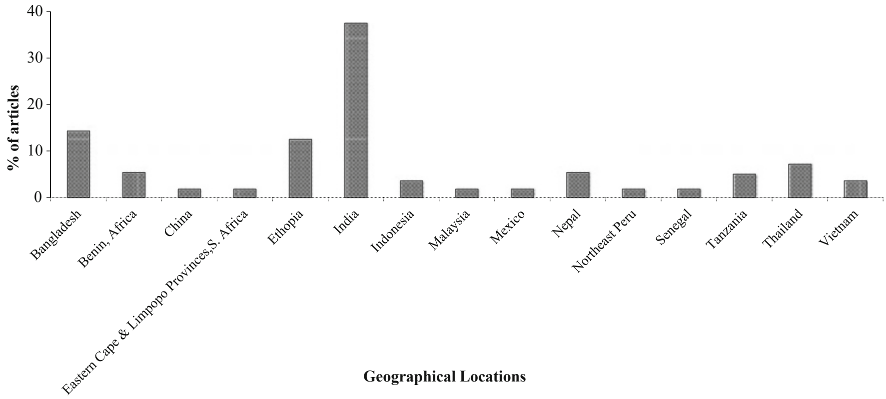

Fig. 12.4 Percentage of HGs articles reported from different tropical regions in the present study

HGs species diversity and richness. Other factors responsible for determining the diversity in the HGs include size of the garden, proximity to urban areas, market access, and geographical and social isolation (Das and Das 2015; Perrault-Archambault and Coomes 2008). For instance, HGs under farming communities that were primarily isolated or remotely located from the major markets were observed to have higher diversity when compared to the HGs farming communities living close to marketplaces or in urban areas (Das and Das 2015). Another critical factor influencing diversity is the differences in cultural practices and management.

Several studies have reported the influence of cultural diversity on the variation of HGs diversity. For example, by Das and Das (2005, 2015), Singh et al. (2014), Nath et al. (2020), Reang et al. (2021a, b) in HGs of the Eastern Himalayan region; Dagar et al. (2014, 2020) in Bay Islands; Kumar (2011) in Kerala; Rahman et al. (2009) in Bangladesh and Huai et al. (2011) in the Southwestern China. In addition, the indigenous traditional knowledge related to plant uses among different communities also influences the management and conservation of different species, thereby affecting HGs diversity (Tangjang and Arunachalam 2009; Reang et al. 2021a, b). Another governing factor is the overall species richness setting of specific regions and/or localities. In essence, with higher parent trees in the nearby natural environment, there is a higher probability that farmers could plant more trees in their HGs. For example, study by Fentahun and Hager (2010) observed a decrease in species diversity with decline in access to the forests.

Other factors such as the dominance of a single species for commercial purposes also influence the diversity in the HGs. In Northeast India, the commercial importance of certain species (*Areca catechu*, *Aquilaria malaccensis*, *Parkia timoriana*, *Hevea brasiliensis,* etc.) over others often acts as a coercion factor for their management and conservation, resulting in the intensification of their cultivation and ultimately causing a decline in the overall HGs diversity (Das and Das 2015; Nath et al. 2020; Reang et al. 2021a, b). In addition to the above-highlighted factors, landscape characteristics such as the farm location altitudes also influence the diversity in the HGs. Studies have reported a sharp decline in the diversity of HGs with the increase in altitude (Fentahun and Hager 2010; Das and Das 2015).

12.4.1 Floristic Composition and Resource Utilization

In the tropical regions, all traditional HGs show high floristic diversities compared with other kinds of agro-ecosystems. From the meta-analyses of the reviewed articles, we found that the total number of plant species ranged from 9 to 602 with a density range of 342–4259 ind. ha^{-1} and Shannon–Wiener diversity index range of 1–4.9 in the tropical HGs (Table 12.1). Based on the literature screened in the present study, the different HGs attributes reported in Asia and elsewhere from the tropical nations worldwide are presented in Table 12.2.

In the Indian state of Mizoram, 333 plant species (133 trees, 92 shrubs and 108 herbs) with an average of 78 plant species per HGs were reported from 90 HGs by Barbhuiya et al. (2016). Their study reported a very high species diversity index score for trees, shrubs and herbs, i.e. 4.76, 4.39 and 4.58, respectively. A study conducted in three villages Liangnyu, Mon and Tanhai from Mon district of Nagaland showed that Tanhai had the maximum number of species (122) and the largest average size of home gardens and 87 species recorded from Mon and 45 species from Liangnyu (Singh et al. 2014). In North Tripura, India, a total of 148 species from 130 genera and 55 families have been inventoried from the HGs of the ethnic Reang communities (Das and Datta 2018). In Upper Assam, India, 393 plant species from 111 families have been reported in HGs (Hazarika et al. 2014), while Saikia and Khan (2016) reported a total of 154 tree species under 109 genera and 53 families from 135 HGs in Upper Assam. In another study (Saikia et al. 2012), altogether 294 plant species belonging to 217 genera and 92 families were reported from Upper Assam. Of the total, as much as 260 plant species were reported as economically important, and the remaining 34 species were reported as weeds and grasses. Das and Das (2005) reported 122 plant species from the traditional HGs of Southern Assam. In the HGs of Cooch Behar, West Bengal, India, a total of 260 plant species were reported among which 53 plant species were utilized for different ethnobotanical applications (Pala et al. 2019). In the HGs of Kerala, India, 127 woody species were reported by Kumar et al. (1994) and 182 plant species by George and

Table 12.1 Descriptive statistics of homestead/garden attributes for tropical regions

Parameter	HG size (ha)	Species number	Density (Ind. ha^{-1})	Shannon–Wiener diversity index (H)
Min	0.003	9	342	1
Max	2.4	602	4259	4.9
Mean	0.42	153	1745.7	2.9
Median	0.14	114	1367.5	3.2
Std. Dev.	0.61	115.9	1454.9	1.13

Table 12.2 Farm size and plant characteristics under tropical homestead gardens

Geographical location	Highest species number reported	H diversity index	Largest HG size (ha) reported	Some commonly reported plant species
India	393	4.76	2.19	*Areca catechu, Artocarpus heterophyllus, Mangifera indica, Psidium guajava*
Bangladesh	419	3.4	0.35	*Areca catechu, Bambusa* species, *Mangifera indica, Artocarpus heterophyllus*, *Musa* species
Nepal	342	4.9	0.43	*Mangifera indica, Luffa aegyptiaca, Neolamarckia cadamba, Musa* species, *Solanum tuberosum*
Indonesia	602	–	2.4	*Mangifera indica, Solanum lycopersicum, Capsicum annuum, Curcuma longa, Musa* species
Malaysia	207	3.61	0.15	*Musa paradisiaca, Cocos nucifera, Carica papaya, Mangifera indica*
Vietnam	84	–	0.1	*Musa paradisiaca, Mangifera indica, Psidium guajava, Ananas comosus, Carica papaya*
Thailand	243	1	0.43	*Mangifera indica, Artocarpus heterophyllus, Psidium guajava, Colocasia esculenta*
China	108	–	0.12	*Rosa chinensis, Armeniaca vulgaris, Capsicum annuum*
Ethiopia	258	3.8	0.5	*Calpurnia aurea, Cordia africana, Tamarindus indica, Ficus vasta*
Benin	323	2.7	–	*Vitellaria paradoxa, Parkia biglobosa, Lannea microcarpa*
Mexico	71	2.2	–	*Coffea arabica, Ardisia compressa, Eupatorium quadrangulare, Pseudolmedia glabrata*
Peru	82	–	1	*Ananas comosus, Anacardium occidentale, Psidium guajava, Inga* spp.

Christopher (2020). In Andaman and Nicobar Islands of India, Dagar (1995) reported uses of 266 MPTs in various agroforestry systems and listed 29 species of vegetables, 16 of fruit bearing, 6 species of pulses, 7 nuts/oil/fats, 6 spices and 14 fodder species cultivated in HGs besides many MPTs retained or planted. Shimrah et al. (2018) identified 73 plant species of economic, social and cultural values belonging to 27 families in the traditional HGs of the Tangkhul community of Ukhrul district, Manipur, India. Among these, vegetables was the largest category (34 species), followed by spices (13 species), fruit crop (12 species), medicinal plants and opportunistic wild crops (10 species each) and others (4 species).

In Kishoreganj, Bangladesh, 62 plant species from 36 families, which included five threatened species with Shannon diversity index range of 2.36–3.39, were reported from the HGs. The majority of these species were utilized as fruit and food (45%), medicinal plants (38.71%), firewood (32.26%) and timber (29%) (Roy et al. 2013). Another study in Jaintapur Upazila of Sylhet district, Bangladesh, reports 15 timber species, 22 horticultural species, 6 medicinal species, 13 annual crops including leafy vegetables, 7 species of spices and 5 species of bamboo along with betel leaf from the ethnic Khasia HGs (Rahman et al. 2009). In the Mymensingh district, Bangladesh, 43 woody perennials and 38 vegetable species were reported from the HGs (Muhammed et al. 2011).

In Nepal, total species diversity was relatively high, ranging from 172 to 257 in the Tarai plains and 224 to 342 in the Hill agro-ecosystems with Shannon diversity index ranging from 3.18 to 3.3 (Gautam et al. 2008). Similarly, other studies in the HGs of Nepal recorded 254 species from 197 genera and 76 families. However, the list excludes the ornamental plants whose number was as high as 210 species (Subedi et al. 2006). Sunwar et al. (2006) reported a comparatively lower number of species than the above studies in the HGs of Nepal, i.e. 165 different crop species. According to their study, the mid-hill revealed higher species diversity (131 species) when compared to the Tarai plains (123 species). In Kampung Masjid Ijok, Perak, Malaysia, a total of 207 plant species corresponding to 78 families were reported from 40 HGs (Ramli et al. 2021). In Kalasin Province, Thailand, a fairly low species diversity of 20 species corresponding to 13 botanical families were reported from the HGs (Cruz-Garcia and Struik 2015), while another study (Panyadee et al. 2016) reported a comparatively higher species number of 94 woody plant, most of which had edible fruits in Northern Thailand. Trinh et al. (2003) reported that in Vietnam, the total number of plant species in HGs ranged from 12 to 103, with the average number of species being 0.7–2.7 per 0.01 ha. In West Java, Indonesia, a single HG was reported with as high as 602 species (Abdoellah et al. 2002), while a moderately high number of plant species (271) were recorded in Central Javanese HGs (Kaswanto and Nakagoshi 2014). A study by Kehlenbeck and Maass (2004) inventoried 149 crop species which mainly comprised fruit, vegetable, spice or medicinal plants in Central Sulawesi, Indonesia.

In Ethiopia, Africa, 38 plant species were reported, of which 12.36% were edible plants, 11.90% income source plants and 8.92% shade plants (Kebebew 2018). The Chagga HGs in Tanzania showed high biodiversity with over 500 species (Hemp 2006). Another study (Feleke 2011) in Southern Ethiopia revealed a moderately high number of plant species (224), while Agize et al. (2013) reported a total of 214 plant species from HGs of Dwaro zone, Southern Ethiopia. Naigaga et al. (2021) reported 96 plant species from Senegal, Africa where 54% were of food species, 40% medicinal, 32% ornamental, 14% commercial, 7% fodder, 4% sacred, 4% ceremonial and 3% cosmetic. When compared to the above studies, Gbedomon et al. (2016) reported a fairly higher number of plant species (323 species from 226 genera and 81 families) from Benin, Africa. In the HGs of Mesoamerica (Southern-central Mexico), 233 plant species were reported, of which 66% were ornamental, 30% edible and 9% medicinal (Blanckaert et al. 2004), while in the humid lowlands of

Mexico, Rico-Gray et al. (1991) recorded 301 trees and shrubs where more priority was given to medicinal plants, i.e. 70% medicinal, 40% apiculture, 30% edible, 19% building, 17% fuel and 12% timber.

12.4.2 *Diversity Vis-à-Vis Size of HGs*

Size of HGs is one crucial factor that influences species diversity (Kumar and Nair 2004). Ramli et al. (2021) reported a greater Shannon–Wiener index score in the large-sized HGs ($H = 3.61$) and a low index score for the small-sized HGs ($H = 1.66$) in Kampung Masjid Ijok, Perak, Malaysia. In contrast, Kumar et al. (1994) reported higher floristic diversity for small HGs (Simpson's diversity index, $D = 0.61$), which declined with an increase in garden size, i.e. medium ($D = 0.44$) and large ($D = 0.46$) in Kerala, India. In another study by Kumar (2011), a similar trend was reported, i.e. the total number of species for the small-, medium- and large-sized HGs being 145, 173 and 138, respectively, in the three districts of Central Kerala, India. Similarly, Sahoo et al. (2010) reported the highest species diversity in the small gardens (81 species) as compared to medium and large HGs (53 and 37 species, respectively) in Mizoram, India. Studies from Latin American HGs also suggest that density and species diversity per unit area was higher for small-sized gardens when compared to the larger ones (María et al. 2008). However, a study by Shimrah et al. (2018) in the Tangkhul HGs of Manipur, India highlighted that the size of garden does not correspond to crop diversity since a great variety of crops can be grown in small areas of HGs. Nevertheless, the above findings reveal that size of HGs has a strong relation with plant diversity conserved, although it could vary from region to region and within different farming communities.

12.5 Management Strategies and Conservation in Homestead Gardens

A close relationship exists between management and functions of traditional HGs. The management of traditional HGs can provision multiple functions and services (Fig. 12.5). However, very few studies focussing on the traditional management of HGs have been conducted globally (Huai and Hamilton 2009), requiring more research and in-depth studies. Blanckaert et al. (2004) classified plants in HGs into three main types according to the intensity of their management (Table 12.3).

HGs in the tropics are traditionally managed and adopted by poor local farmers rather than through agroforestry research (Nair 2001). Therefore, not necessarily all farmers follow similar HGs development and management trends. The HGs managers are perpetual 'experimenters'. They are constantly testing and trying new species and varieties and their management (Niñez 1987). So, HGs are associated

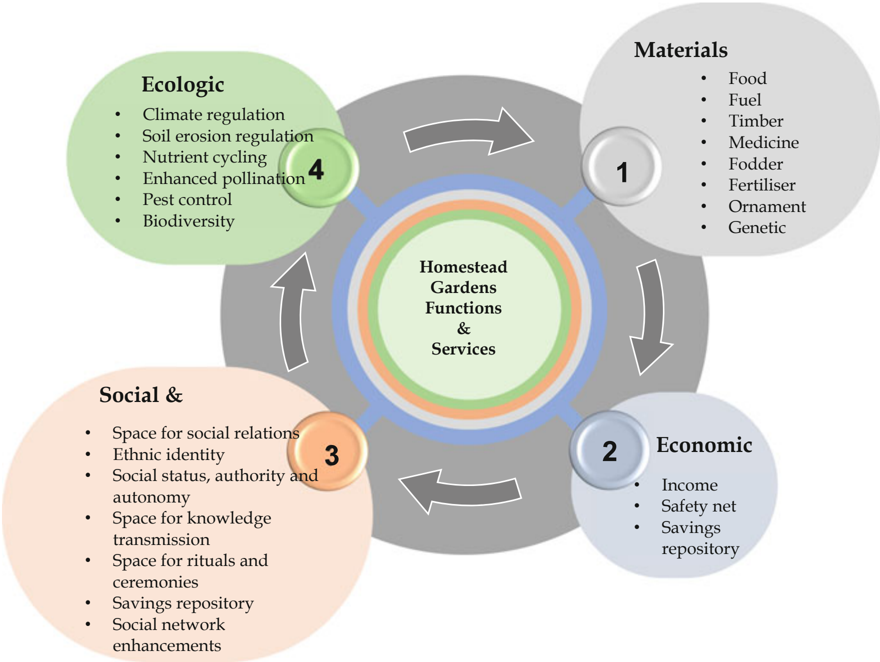

Fig. 12.5 Functions and services provisioned from management of traditional homestead gardens

Table 12.3 Plant types in homestead gardens based on the plant management

Plant types	Management practices
Cultivated	Under intensive management
Protected	Spontaneously growing or transplanted from elsewhere, the owner takes measures to protect or encourage them
Spared	Naturally growing, left unweeded

with vast indigenous knowledge on plant species management and their sustainable use. A new species may be chosen by the farmer because of its properties, i.e. food, medicine, fuel wood, ornamental, religious, ornamental, and based on self-instinct or information passed on by elders or neighbours and relatives. For example, the ethnic Hmar farmers of Southern Assam, India, are known to store vast indigenous knowledge about the propagation and management of many MPTs learned through a series of farm transitions after long-term farming experiences (Reang et al. 2021a). Throughout the farm transitions, one species is being replaced by other favourable MPTs for maximizing household benefits and income.

The traditional management under the tropical HGs is also characterized by meagre input and simple technology (Niñez 1987). In most cases, human labour is the only input under such traditionally managed land-use systems (Dash and Misra 2001) where genders often play differential roles. For instance, women and children are the main labour forces in traditional HGs management in Bangladesh (Ali 2005), but in Yemen, children work less in HGs (Ceccolini 2002). In contrast, gardening in India is dominated by the male members (Dash and Misra 2001). The labour input or invested in HGs increase with decreasing garden size owing to more intensive production. For example, the mean daily labour inputs in HGs per 0.01 ha could vary from about 1 min. (Dash and Misra 2001), 2–4 min. (Ali 2005), and 5–10 min. (Trinh et al. 2003) all the way up to 9–77 min. in the intensively managed gardens (Stoler 1978).

12.5.1 Challenges in the Management System

The concern for many HGs practices arises from the gradual fading of traditional lifestyles over time. Presently, many traditional HGs are showing a trend of a shift from the conventional subsistence-oriented agriculture to a market economy-oriented system (Peyre et al. 2006). This change in trend or shift is likely to threaten the potential characteristics of the traditional HGs and their allied services. A possible result is that species richness under the traditional HGs could be altered or changed along with the vanishing traditional agro-ecosystems. For instance, the Hani community in South Yunnan, China, introduced lots of wild plants from their shifting fallows and fallow forests in HGs for contributing greatly to households' economic income. Additionally, traditional management of HGs is also facing challenges along with variations in physical and socio-economic conditions. Peyre et al. (2006) reported that 33% of HGs have embraced modern technology in their farming practices, while 50% of HGs still retained the traditional management practices in Palghat district, Kerala, India. Thus, the dynamics of HGs are always an outcome of the combination of many factors. However, there are minimal studies on these issues (Huai and Hamilton 2009).

12.5.2 Traditional Management Systems

This section attempts to provide a brief overview of a few following traditional management practices under the HGs systems reported in India and elsewhere. Besides, different management strategies under traditional HGs reported by Mohri et al. (2013) have been given in Table 12.4.

1. In general, majority management practices concern manipulating the tree environment rather than the tree species itself. A typical example is the management practices reported in HGs of Kerala, India (Peyre et al. 2006). Sanitary pruning, rejuvenation and canopy pruning to increase light penetration and cutting of low branches are occasionally done under this system. On the other hand, practices like weeding, fertilization and crop spacing are more common. The cultivation

Table 12.4 Various farm management regimes adopted in different tropical HG systems

Time scale	Indonesia (*Javanese* HGs)	Sri Lanka (*Kandyan* HGs)	Vietnam (*VAC* HGs)
Time spent in HGs	1 h/week/0.01 ha	57 man days annually	220 days annually
Cutting/ harvesting cycle	Irregular work schedule	Continuous depending on different crop output	Continuous
Labour invested	Small amount of time	Relatively small amount of labour	Relatively more time
Labour division	Male: Farm preparation, cultivation of tree crops, harvesting and marketing; female: Cultivation of annual crops, harvesting	Relatively equal labour by males and females	Family member manages farming activities

practices include utilization of chemical fertilizers and insecticides, systematic weeding, organic fertilization and row arrangement of trees. The most intensively managed species include *Cocos nucifera*, *Hevea brasiliensis* and *Areca catechu*. These crops are relatively more protected from competitors and are the only crops that receive watering. Other fruit trees, neem (*Azadirachta indica*) and timber species (*Tectona grandis*) intercropped in the gardens receive relatively lesser attention.

The different HG types can be arranged along a gradient of management intensity. The small-sized HGs are characterized by low-to-medium management inputs, whereas the medium- to big-sized HG types were subjected to more intensive management. In the case of larger HGs, row planting was dominant under the HGs practices in Kerala, India.

2. For centuries, the indigenous management of HGs by the ethnic Hmar communities in Southern Assam, India, was reported by Reang et al. (2021a). The management strategy under this system is unique as it combines annual crops and perennial pineapple (*Ananas comosus*) crops cultivated with remnants of fallow tree species and the subsequent management intensification of more economically viable trees replacing the natural fallow trees in the farms. Traditional management involved the clearing of fallow vegetation for farm preparation through slash-and-burn. All male and female household members are engaged in the cultivation and management process, with work division allotted accordingly through different management phases. No-tillage or external fertilizer input is done as a management strategy. The indigenous technique involves retaining matured and large trees on the farms to provide shade to the understory crops and for soil erosion control. Multiple annual crops and pineapple are intercropped with the large trees on the same piece of land. Weeding, on average, was done twice or thrice annually. Girdling or ring barking of the retained fallow trees is practised to ensure no damage to the understory crops, optimum shade, weed suppression and nutrient supply. The most preferred tree species for shade was *Albizia procera*. The Hmar farmers applied traditional knowledge for tree

species selection through long-term farming experience. With the farm transitions over time, intensive management of MPTs (*Areca catechu, Musa* species*, Parkia timoriana, Aquilaria malaccensis*, etc.) is carried out. These MPTs are usually planted in rows and potentially serve for both household (food, fuel wood, medicine and economy) and environmental benefits (shade, soil binding, windbreaks and live fences).

3. Rahman et al. (2009) reported the traditional management practices of betel leaf (*Piper betel*) cultivation by the ethnic 'Khasia' tribes in the HGs of Bangladesh. The tribe rely on indigenous knowledge and technology to cultivate their crops. Farm preparation involves clearing the land area to expose the topsoil. All cut and fell vegetation were gathered around the base of the host trees (mulching). Application of organic fertilizer is seldom made under these management practices. The tribe used vegetative parts as propagating materials. Plucking of betel leaves starts after 2–2.5 years of planting. During this period, regular weeding was practised. Weeding frequency varied three to four times annually. Pruning of host trees is done every year during the pre-monsoon period. Both male and female members are involved in the production system. No specific planting pattern, spacing and species selection for the host plant, protection from insects and pests were conducted. Nonetheless, the tribes planted a wide range of host tree species for growing the betel leaves. Along with the host trees, other crops cultivated include *Curcuma longa, Zingiber officinale, Elettaria cardamomum, Citrus limon, Ananas comosus* and climbing vegetables.

12.6 Conservation Importance of Homestead Gardens

HGs have great potential in preserving plant and animal diversity (Deb 2020; Yashmita-Ulman et al. 2021; Reang et al. 2021a, b). They have long been seen as one of the most effective measure for biodiversity conservation (Roy et al. 2013). A study by Reang et al. (2021b) recorded a higher number of tree species being conserved under the traditional HGs compared to their nearby native forests in Mizoram and Southern Assam, India. According to Yashmita-Ulman et al. (2021), traditional HGs harbour rich plant diversity and mimic natural forests by conserving rare and threatened species. They are considered living gene banks and reservoirs of plant genetic resources that preserve landraces, cultivars, rare and endangered species, and species neglected in larger ecosystems (Das and Das 2015). However, the selection and maintenance of species diversity by farmers' in the HGs does not intend for plant conservation but arises because of their multiple uses and long-term product benefits. Farmers' perceived most importance for HG plant species conservation is related to fruit and food, building materials, subsistence family income and source of firewood. Several studies around the tropics have highlighted the importance of HGs plant conservation relating to the farmer's daily need (Uddin et al. 2001; Das and Das 2005; Gautam et al. 2008; Rahman et al. 2009;

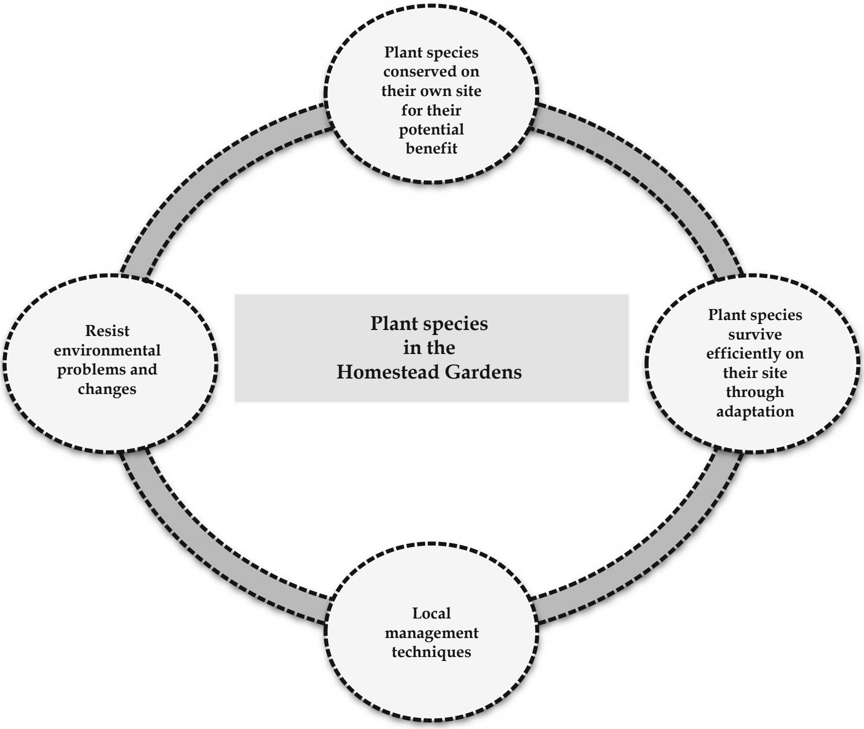

Fig. 12.6 Homestead gardens for in-situ conservation of plant diversity

Reang et al. 2021a, b). According to Roy et al. (2013), another possible reason for the conservation of trees by farmers is due to their role in protecting the homestead land against water-induced soil erosion. A study by Reang et al. (2021a) also reported the use and management of tree species in HGs for soil conservation in the sloped areas of Southern Assam, India.

Nevertheless, due to the gradual decline in natural forests, rural populace that are dependent on the forests around them tend to cultivate more plant species in their HGs and conserve them for deriving their daily livelihood needs. Hence, HGs have mainly been highlighted as an important site for in-situ conservation of plant diversity (Watson and Eyzaguirre 2002). Some opined in their possibility of maintaining species in ex-situ (Kabir and Webb 2008). The role of HGs for in-situ conservation of plant species has been presented in Fig. 12.6 (modified from Semu 2018). The presence of fruit and timber tree species in the HGs diversity indicates their potential as in-situ conservation sites. On the other hand, HGs with an important repository of underutilized trees could represent conservation and preservation sites of naturally regenerating forest tree species. For example, *A. malaccensis*, a critically Endangered and Red Listed tree species of India, is widely domesticated in the HGs of Upper Assam and Barak valley, India (Saikia et al. 2012; Nath et al.

2020; Reang et al. 2021a). In Assam, farmers preserve and manage *A. malaccensis* in the HGs due to their high commercial value, highlighting the concept of biodiversity conservation through use. Saikia et al. (2012) reported the species (*A. malaccensis*) as most dominant (1414 trees ha^{-1}) in HGs of Upper Assam reflecting the overall level of active domestication. Another such example is the underutilized tree species, *Parkia timoriana* (economically important species), which is no longer found in natural forests and is being preserved and managed for home consumption and market sale in the HGs of Southern Assam, India (Reang et al. 2021a).

The conservation value of HGs as repositories of underutilized, native and endangered plants has also been highlighted by several other studies worldwide. In the HGs of Southern Assam, out of the total 161 species inventoried, 86% are reported as native species to the region (Das and Das 2015). Their study highlighted that commonness of native plant species in the households highlights the significance of HGs for conservation. Borgohain et al. (2021) reported different IUCN Red Lists of conservation species categorized under threatened (1 sp.), vulnerable (3 sp.), endangered (3 sp.), data deficient (9 sp.) and critical (1 sp.) from HGs of Assam, India. In a study by Saikia and Khan (2016), the majority (79%) of the plant species were reported as indigenous (to India), while the rest (21%) as aliens (naturalized and cultivated exotics) by origin in HGs of Upper Assam. Panyadee et al. (2016) reported 52% of plant species as native and 48% as exotic in HGs of Northern Thailand. Roy et al. (2013) documented 62 plant species, of which 5 were identified as threatened species from HGs of Bangladesh. A botanical survey in more than 400 home gardens totalling 45.2 ha in South-western Bangladesh revealed 419 species (59% as native), of which six species were on the IUCN Red List for the country (Kabir and Webb 2008). In Benin, Africa, 20 wild crop relatives and 12 threatened species were recorded from HGs, mainly conserved to be used for food and medicinal purposes (Salako et al. 2013).

HGs are also reported to attract several bird species and animals, highlighting their importance in animal conservation (Rahman et al. 2009; Roy et al. 2013; Mukul 2014). A study by Mukul (2014) reported a total of 27 mammalian species and 53 bird species in HGs of Bangladesh. In his study, higher diversity of birds (31 species) was reported from betel-vine dominated HGs when compared to the natural forests (23 species). However, mammal diversity was reported with a reverse trend, i.e. forest (15 species) and betel-based HGs (11 species). Some birds species reported in tropical HGs of Bangladesh are *Streptopelia chinensis, Psittacula krameri, Eudynamys scolopaceus, Micropternus brachyurus, Dinopium benghalense, Oriolus xanthornus, Dicrurus macrocercus, Acridotheres tristis, Corvus splendens*, etc. (Roy et al. 2013). These birds collect their food from the plants and find shelter in the HGs and in return help in pollination. Thus, these conservation systems should be reserved to continue ensuring the daily needs of the rural poor populations and conserving biodiversity as well.

12.7 Conclusion and Recommendations

It is concluded that ethnic HGs are the sites of rich species composition and plant diversity firmly bound by the traditional wisdom on nutritional and livelihood security. Gradual replacement of traditional practices with modern farming technology and the considerable changes in the management practices from subsistence to market-oriented systems over time could raise serious doubts regarding the sustainability and productivity of these traditional systems. Hence, there is a need to develop management techniques and/or models that are time-tested and suitably modified for different HGs without compromising the sustainability and productivity of these unique systems.

The authors believe that the limitation of HGs practices lies in the system being primarily embraced or adopted by the resource-poor/small-scale farmers mainly in the rural areas. As such, despite the system being a great alternative to natural forest, it may not globally stand out in terms of its total spatial coverage. Therefore, HGs practices may be implemented out in land under restoration and gaps under urban set-ups for increased tree cover and its optimum production and services. Another arising concern is the change in the land-use systems of these traditional HGs in recent decades. The HGs managers may be aided with inter alia incentives for practising and managing these traditional farming systems via proper pricing, loans, credit, insurance, marketing, etc. The incentives provided would help motivate and encourage the local farmers to manage these important land-use systems more sustainably and efficiently.

Furthermore, appropriate and proper training may be given to the HGs managers about the systematic agroforestry farming system. The local governing organizations and officials can open up provisions for storing, processing and managing raw materials to facilitate better marketing of HGs products through infrastructural facilities and by setting up small-scale factories and cottage industries in different pockets in rural areas. Modern technologies for processing and value-addition that are appropriate to specific systems can be introduced to the farmers to increase the system's overall productivity and profitability. Policymakers and researchers can help and assist farmers through proper direction for selecting suitable plant species (habitat and climatic conditions) in HGs for greater structure, diversity and composition. In this respect, forest departments and other local governments could play an important role by setting up nurseries, providing seedlings of important plant species, and fencing materials for their management. Additionally, loan schemes providing cash for domestic livestock purchases to the farmers could provide potential security during an incidence of crop failure.

References

Abdoellah OS (1990) Homegardens in Java and their future development. In: Landauer K, Brazil M (eds) Tropical home gardens. United Nations University Press, Tokyo, pp 69–79

Abdoellah OS, Parikesit GB, Hadikusumah HY (2002) Home gardens in the Upper Citarum Watershed, West Java: a challenge for in situ conservation of plant genetic resources. In: Watson JM, Eyzaguirre PB (eds) Home gardens and in-situ conservation of plant genetic resources in farming systems. IPGRI, DSE and GTZ, Proc of the second international home garden workshop, Witzenhausen, Germany, pp 140–147

Agize M, Demissew S, Asfaw Z (2013) Indigenous knowledge on management of home gardens and plants in Loma and Gena Bosa districts (weredas) of Dawro Zone, Southern Ethiopia: plant biodiversity conservation, sustainable utilization and environmental protection. Int J Sci Basic Appl Res 10:63–99

Alam M, Furukawa Y (2010) Agroforestry homegardens in rural landscapes of Bangladesh. In: Be'lair C, Ichikawa K, Wong BYL, Mulongoy KJ (eds) Sustainable use of biological diversity in socioecological production landscapes. Technical series no. 52. Secretariat of the Convention on Biological Diversity, Montreal, pp 120–124

Ali AM (2005) Homegardens in smallholder farming systems: examples from Bangladesh. Hum Ecol 33(2):245–270

Altieri MA (1995) Agroecology: the science of sustainable agriculture, 2nd edn. Westview Press

Barbhuiya AR, Sahoo UK, Upadhyaya K (2016) Plant diversity in the indigenous home gardens in the Eastern Himalayan Region of Mizoram, Northeast India. Econ Bot 70(2):115–131

Blanckaert I, Swennen RL, Flores PM, Lopez RI, Saade RL (2004) Floristic composition, plant uses and management practices in homegardens of San Rafael Coxcatlan, valley of Tehuacan-Cuicatlan, Mexico. J Arid Environ 57:39–62

Borgohain MP, Teron R, Tamuli AK (2021) Conservation and management of plant bioresources by the Tai Phake of Assam: role of home garden and monastery. J Adv Plant Sci 11(1):13–28

Brierley JS (1985) West Indian kitchen gardens: a historical perspective with current insights from Grenada. Food Nutr Bull 7(3):52–60

Ceccolini L (2002) The homegardens of Soqotra island, Yemen: an example of agroforestry approach to multiple land-use in an isolated location. Agrofor Syst 56(2):107–115

Coomes OT, Ban N (2004) Cultivated plant species diversity in home gardens of an amazonian peasant village in Northeastern Peru. Econ Bot 58(3):420–434

Cruz-Garcia GS, Struik PC (2015) Spatial and seasonal diversity of wild food plants in home gardens of Northeast Thailand. Econ Bot 69(2):99–113

Dagar JC (1995) Agroforestry systems for the Andaman and Nicobar Islands. Int Tree Crops J 8: 107–128

Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, pp 185–232

Dagar JC, Gangaiah B, Gupta SR (2020) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, pp 367–424

Das T, Das AK (2005) Inventorying plant biodiversity in homegardens: a case study in Barak Valley, Assam, North East India. Curr Sci 89(1):155–163

Das T, Das AK (2015) Conservation of plant diversity in rural homegardens with cultural and geographical variation in three districts of Barak Valley, Northeast India. Econ Bot 69:57–71

Das D, Datta BK (2018) An assessment of plant diversity in Home gardens of Reang community of Tripura. Pleione 12(2):208–222

Dash SS, Misra MK (2001) Studies on hill agro-ecosystems of three tribal villages on the Eastern Ghats of Orissa, India. Agric Ecosyst Environ 86(3):287–302

Deb S (2020) Traditional agroforestry systems of Northeast India. In: Socio-economic and eco-biological dimensions in resource use and conservation. Springer, Cham, pp 103–115
Debbarma J, Deb D, Deb S (2015) Tree diversity and sociocultural significance of homegardens in the Baramura range, Tripura, North-east India. For Trees Livelihoods 25(1):33–40
FAO (2017) The future of food and agriculture—trends and challenges. FAO, Rome
Feleke W (2011) Home gardens and spices of Basketo and Kafa (South west Ethiopia): plant diversity, product valorization and implications to biodiversity conservation. Ph.D. Thesis, Addis Ababa University, Addis Ababa
Fentahun M, Hager H (2010) Integration of indigenous wild woody perennial edible fruit bearing species in the agricultural landscapes of Amhara region Ethiopia. Agrofor Syst 78(1):79–95
Fernandes EC, Nair PKR (1986) An evaluation of the structure and function of tropical homegardens. Agric Syst 21(4):279–310
Fernandes EC, Oktingati A, Maghembe J (1984) The Chagga homegardens: a multistoried agroforestry cropping system on Mt. Kilimanjaro (Northern Tanzania). Agrofor Syst 2:73–86
Gautam R, Sthapit B, Subedi A, Poudel D, Shrestha P, Eyzaguirre P (2008) Home gardens management of key species in Nepal: a way to maximize the use of useful diversity for the well-being of poor farmers. Plant Genet Resour 7(2):142–153
Gbedomon RC, Assogbadjo AE, Salako VK, Fandohan AB, Kakaï RG (2016) Exploring the spatial configurations of home gardens in Benin. Sci Hortic 213:13–23
George MV, Christopher G (2020) Structure, diversity and utilization of plant species in tribal homegardens of Kerala, India. Agrofor Syst 94(1):297–307
Hazarika P, Biswas SC, Kalita RK (2014) A case study on people's choice conservation of biodiversity in homesteads of Assam, India. Int Res J Biol Sci 3(1):89–94
Hemp A (2006) The banana forests of Kilimanjaro: biodiversity and conservation of the Chagga homegardens. Biodivers Conserv 15(4):1193–1217
Hemp C, Hemp A (2008) The Chagga home gardens on Kilimanjaro. MRI Global Change research Network in Africa. p 6
Huai H, Hamilton A (2009) Characteristics and functions of traditional homegardens: a review. Front Biol China 4(2):151–157
Huai H, Xu W, Wen G, Bai W (2011) Comparison of the homegardens of eight cultural groups in Jinping County, Southwest China. Econ Bot 65(4):345–355
Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76(1):1–10
Kabir ME, Webb EL (2008) Floristics and structure of southwestern Bangladesh homegardens. Int J Biodivers Sci Manag 3:1–11
Kanianska R (2016) Agriculture and its impact on land-use, environment, and ecosystem services. In: Landscape ecology—the influences of land use and anthropogenic impacts of landscape creation. Intech Open Limited, London, pp 1–26
Kaswanto RL, Nakagoshi N (2014) Landscape ecology-based approach for assessing pekarangan condition to preserve protected area in West Java. In: Designing low carbon societies in landscapes. Springer, Tokyo, pp 289–311
Kebebew M (2018) Diversity and management of useful homegardens plant species in Arba Minch Town, Southern Ethiopia: implication for plant diversity conservation and food security. Int J Econ Plants 5(3):137–148
Kehlenbeck K, Maass BL (2004) Crop diversity and classification of homegardens in Central Sulawesi, Indonesia. Agrofor Syst 63(1):53–62
Kumar BM (2011) Species richness and aboveground carbon stocks in the homegardens of central Kerala, India. Agric Ecosyst Environ 140(3–4):430–440
Kumar BM, Nair PKR (2004) The enigma of tropical homegardens. Agrofor Syst 61(1):135–152
Kumar BM, George SJ, Chinnamani S (1994) Diversity, structure and standing stock of wood in the homegardens of Kerala in peninsular India. Agrofor Syst 25(3):243–262
María TP, Pagaza-Calderón EM, Martínez-Ballesté A, Maldonado-Almanza B, Saynes A, Pacheco RM (2008) Home gardens as an alternative for sustainability: challenges and perspectives in

Latin America. In: Paulino de Albuquerque U, Ramos MA (eds) Current topics in ethnobotany, pp 1–25. ISBN: 978-81-308-0243-5
Masum KM, Alam MS, Abdullah-Al-Mamun MM (2008) Ecological and economical significance of homestead forest to the household of the offshore island in Bangladesh. J For Res 19(4): 307–310
Méndez VE, Lok R, Somarriba E (2001) Interdisciplinary analysis of homegardens in Nicaragua: micro-zonation, plant use and socioeconomic importance. Agrofor Syst 51(2):85–96
Millet-E-Mustafa M (1996) The ecology and management of traditional homegarden in Bangladesh. Ph.D. thesis, University of Wales, Bangor, UK. (ICRAF) Nairobi, Kenya
Mohri H, Lahoti S, Saito O, Mahalingam A, Gunatilleke N, Hitinayake G, Takeuchi K, Herath S (2013) Assessment of ecosystem services in homegarden systems in Indonesia, Sri Lanka, and Vietnam. Ecosyst Serv 5:124–136
Muhammed N, Masum MFH, Hossain MM, Chakma S, Oesten G, von Detten R (2011) Floral composition and biodiversity conservation in homestead forests in Mymensingh, Bangladesh. Int J Biodivers Sci Ecosyst Serv Manag 7(4):247–257
Mukul SA (2014) Biodiversity conservation and ecosystem functions of traditional agroforestry systems: case study from three tribal communities in and around Lawachara National Park. In: Forest conservation in protected areas of Bangladesh. Springer, Cham, pp 171–179
Naigaga H, Ssekandi J, Ngom A, Sseremba G, Mbaye MS, Noba K (2021) Ethnobotanical knowledge of home garden plant species and its effect on home garden plant diversity in Thies region of Senegal. Environ Dev Sustain 23(5):7524–7536
Nair PKR (1989) Agroforestry systems, practices and technologies. In: Agroforestry systems in the tropics. Kluwer academic publishers, Dordrecht
Nair PKR (1993) State-of-the-art of agroforestry research and education. Agrofor Syst 23(2–3): 95–119
Nair PKR (2001) Do tropical homegardens elude science, or is it the other way around? Agrofor Syst 53:239–245
Nair PKR, Buresh RJ, Mugendi DN, Latt CR (1999) Nutrient cycling in tropical agroforestry systems: myths and science. In: Buck LE, Lassoie JP, Fernandes ECM (eds) Agroforestry in sustainable agricultural systems. CRC Press, Boca Raton, FL, pp 1–31
Nath TK, Aziz N, Inoue M (2015) Contribution of homestead forests to rural economy and climate change mitigation: a study from the ecologically critical area of Cox's Bazar—Teknaf Peninsula, Bangladesh. Small-Scale For 14(1):1–18
Nath PC, Nath AJ, Sileshi GW, Das AK (2020) Stand structure and functional attributes of agarwood (*Aquilaria malaccensis* Lam.) based smallholder farms in Northeast India. Trees For People 2:100027
Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Prod 281:124831
Niñez V (1987) Household gardens: theoretical and policy considerations. Agric Syst 23:167–186
Padoch C, De Jong W (1991) The house gardens of Santa Rosa: diversity and variability in an amazonian agricultural system. Econ Bot 45(2):161–175
Pala NA, Sarkar BC, Shukla G, Chettri N, Deb S, Bhat JA, Chakravarty S (2019) Floristic composition and utilization of ethnomedicinal plant species in home gardens of the Eastern Himalaya. J Ethnobiol Ethnomed 15(1):1–16
Panyadee P, Balslev H, Wangpakapattanawong P, Inta A (2016) Woody plant diversity in urban homegardens in Northern Thailand. Econ Bot 70(3):285–302
Perrault-Archambault M, Coomes OT (2008) Distribution of agrobiodiversity in homegardens along the Corrientes River, Peruvian Amazon. Econ Bot 62(2):109–126
Peyre A, Guidal A, Wiersum KF, Bongers F (2006) Dynamics of homegarden structure and function in Kerala, India. Agrofor Syst 66:101–115

Rahman M, Rahman MM, Islam M (2009) Financial viability and conservation role of betel leaf based agroforestry: an indigenous hill farming system of Khasia community in Bangladesh. J For Res 20(2):131–136

Ramli MR, Milow P, Malek S (2021) Species composition, diversity and traditional uses of plants in homegardens in Kampung Masjid Ijok, Perak, Malaysia. Biodivers J Biol Div 22(4)

Reang D, Hazarika A, Sileshi GW, Pandey R, Das AK, Nath AJ (2021a) Assessing tree diversity and carbon storage during land use transitioning from shifting cultivation to indigenous agroforestry systems: implications for REDD+ initiatives. J Environ Manag 298:113470

Reang D, Sahoo UK, Giri K, Hazarika A, Nath AJ (2021b) Ethnic homestead forests of North East India revealed as diverse land-use systems. Agrofor Syst 96:465–478. https://doi.org/10.1007/s10457-021-00700-z

Reijntjes C, Haverkort B, Waters-Bayer A (1992) Farming for the future: an introduction to low-external-input and sustainable agriculture. ILEIA, Leusden

Rico-Gray V, Chemás A, Mandujano S (1991) Uses of tropical deciduous forest species by the Yucatecan Maya. Agrofor Syst 14(2):149–161

Roy B, Rahman M, Fardusi MJ (2013) Status, diversity, and traditional uses of homestead gardens in Northern Bangladesh: a means of sustainable biodiversity conservation. Int Schol Res Notices 2013:1–11

Sahoo UK, Rocky P, Vanlalhriatpuia K, Upadhyaya K (2010) Structural diversity and functional dynamism of traditional home gardens of North-East India. The Bioscan 1:159–171

Saikia P, Khan ML (2016) Tree species diversity and its population and regeneration status in homegardens of Upper Assam, Northeast India. J For Environ Sci 32(2):129–139

Saikia P, Choudhury BI, Khan ML (2012) Floristic composition and plant utilization pattern in homegardens of Upper Assam, India. Trop Ecol 53(1):105–118

Salako VK, Fandohan AB, Kassa B, Assogbadjo AE, Idohou AFR, Gbedomon RC, Chakeredza S, Dulloo ME, Kakaï RG (2013) Home gardens: an assessment of their biodiversity and potential contribution to conservation of threatened species and crop wild relatives in Benin. Genet Resour Crop Evol 61(2):313–330

Santoro A, Venturi M, Bertani R, Agnoletti M (2020) A review of the role of forests and agroforestry systems in the FAO globally important agricultural heritage systems (GIAHS) programme. Forests 11(8):860

Semu AA (2018) The study of homegarden agrobiodiversity, practices of homegardening and its role for in-situ conservation of plant biodiversity in Eastern Hararghe, Kombolcha Town Oromia Regional State Ethiopia. Open J For 8(02):229

Shimrah T, Lungleng P, Shimrah C, Khuman YSC, Varah F (2018) Role of traditional homegardens in biodiversity conservation and socioecological significance in Tangkhul community in Northeast India. Trop Ecol 59(3):533–539

Singh AK, Arunachalam A, Ngachan SV, Mohapatra KP, Dagar JC (2014) From shifting cultivation to integrating farming: experience of agroforestry development in the Northeastern Himalayan region. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, pp 57–86

Smidt SJ, Haacker EMK, Kendall AD et al (2016) Complex water management in modern agriculture: trends in the water-energy-food nexus over the High Plains Aquifer. Sci Total Environ 566-567:988–1001

Soemarwoto O (1987) Homegardens: a traditional agroforestry system with a promising future. In: Agroforestry: a decade of development, pp 157–170

Southern AJ (1994) Acquisition of indigenous ecological knowledge about forest gardens in Kandy district, Sri Lanka. M.Phil. Dissertation, University of Wales, Bangor, UK

Stoler A (1978) Garden use and household economy in rural Java. Bull Indones Econ Stud 14(2):85–101

Subedi A, Suwal R, Gautam R, Sunwar S, Shrestha P (2006) Status and composition of plant genetic diversity in Nepalese home gardens. In: Gome gardens in Nepal: proceeding of a workshop on "Enhancing the contribution of home garden to on-farm management of plant genetic resources and to improve the livelihoods of Nepalese farmers: lessons learned and policy implications", 6–7 August 2004, Pokhara, Nepal. LI-BIRD, Bioversity International and SDC. Local Initiatives for Biodiversity 324, p 72

Sunwar S, Thornström CG, Subedi A, Bystrom M (2006) Home gardens in western Nepal: opportunities and challenges for on-farm management of agrobiodiversity. Biodivers Conserv 15(13):4211–4238

Tangjang S, Arunachalam A (2009) Role of traditional homegarden systems in Northeast India. Indian J Tradit Knowl 8(1):47–50

Trinh LN, Watson JW, Hue NN, De NN, Minh NV, Chu P, Sthapit BR, Eyzaguirre PB (2003) Agrobiodiversity conservation and development in Vietnamese home gardens. Agric Ecosyst Environ 97(1–3):317–344

Uddin MS, Rahman MJ, Mannan MA (2001) Plant biodiversity in the homesteads of saline area of Southern Bangladesh. In: Haq MF, Hasan MK, Asaduzzaman SM, Ali MY (eds) Proceedings of national workshop on agroforestry research development of agroforestry research in Bangladesh, Gazipur, Bangladesh, pp 45–54

von Grebmer K, Bernstein J, Delgado C, Smith D, Wiemers M, Schiffer T, Hanano A, Towey O, Ní Chéilleachair R, Foley C, Gitter S, Ekstrom K, Fritschel H (2021) 2021 Global Hunger Index: hunger and food systems in conflict settings. Welthungerhilfe, Bonn

Watson JW, Eyzaguirre PB (eds) (2002) Homegardens and in situ conservation of plant genetic resources in farming systems. Proceedings of the second international home gardens workshop, 17–19 July 2001, Witzenhausen, Federal Republic of Germany. IPGRI, Rome

Yashmita-Ulman SM, Kumar A, Sharma M (2021) Conservation of plant diversity in agroforestry systems in a biodiversity hotspot region of Northeast India. Agric Res 17:1–3

Chapter 13
Agroforestry for Plant Diversity and Livelihood Security in Southwest Asia

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Abstract Agroforestry systems deliver livelihood security and multiple ecosystem services to sustain societies and environments. Many multipurpose forest trees with food, timber, medicinal, and industrial values have been introduced in different agroforestry systems in many countries of southwest Asia to sustain livelihood and environmental security. Depending upon the need and environmental conditions of a particular country, the tree species have been identified and selected for growing as agroforestry tree component. The main agroforestry systems distributed in the Southwest Asia region are agrisilvicultural systems, with mainly trees such as chestnut (*Castanea sativa*), jujube (*Ziziphus lotus*), date palm (*Phoenix dactylifera*), and fruiting pine (*Pinus pinea*); silvopastoral systems, with carob (*Ceratonia siliqua*) and Euphrates poplar (*Populus euphratica*) trees; and agrosilvopastoral systems, with tree species of mahlab (*Cerasus mahaleb*), sumac (*Rhus coriaria*), laurel (*Laurus nobilis*), and mangroves. In addition, the systems of entomoforestry with Christ's thorn jujube (*Ziziphus spina-christi*) and carob are also prominent. Practices such as wind breaks and shelter belts, riparian forest buffers, alley cropping, and forest farming are also adopted in some countries in Southwest Asia region. In this chapter, the role of these agroforestry systems in livelihood and food security, and the environmental services they provide are discussed, and the future thrust of agroforestry and forest plans development is recommended.

Keywords Agroforestry systems · Southwest Asia · Livelihood security · Environmental services · Plant diversity

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13.1 Introduction

Since the term "Agroforestry" was coined in 1977, it has been variously defined, but the basic concept that is common to all diverse agroforestry practices is the purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit (Nair et al. 2021). Today, agroforestry represents the modern, science-based approach to harnessing the sustainability attributes and production benefits of time-tested practices of integrating trees in agricultural systems for a variety of objectives. It is now considered a problem-solving science particularly to rehabilitate the degraded ecologies, rendering environmental services and mitigating climate change. Its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use has received increasing attention in development programs and paradigms around the world (Nair et al. 2021).

Land under the agroforestry systems in West Asia and North Africa is estimated at 0.1 million km^2 (Zomer et al. 2014). Agroforestry systems can be more beneficial than traditional methods of agricultural production and forestry, as they can provide greater productivity, economic benefits, and greater diversity of environmental goods and services. Biodiversity in agroforestry systems is usually wider than it is in conventional agricultural systems. The presence of two or more interacting plant species in a given area creates a more multifaceted diverse habitat that can support different groups of birds, insects, and other animals. Depending on the spread of the application, the potential agroforestry impacts might include poverty alleviation by increasing trees related products, such as wood production and many others for domestic consumption and selling, contribution to food security by restoring soil fertility enabling cultivation of diversified food crops, obtaining clean water by reducing the flow of nutrients and pollutants, facing global warming and the threat of food shortage by increasing the volume of resistant to drought trees and the subsequent production of edible fruits, nuts and oils, reducing deforestation and pressure on forested lands by providing firewood grown in the fields, reducing or eliminating the need for toxic chemicals (insecticides, herbicides, etc.), improving human nutrition, through variety of agricultural crops production, and provides an expanding area for medicinal plants and herbs cultivation, in particular, where the access to mainstream medicine is limited. Huge information has been generated on tropical agroforestry systems as compared to other regions and very little information is found for north-west Asia (Tolunay et al. 2007; Qureshi and Ismail 2017). Indeed, the region is one of the least studied although there are many traditional agroforestry practices. Documentation of the traditional practices and the indigenous ecological knowledge associated with these practices and multipurpose trees used in these practices, is timely and of utmost importance to have better management and inform good policy. Therefore, the objectives of this chapter are to (1) document the relevant information on multipurpose tree species and agroforestry systems of this region; and (2) provide evidence for improvement in plant diversity and livelihood security through agroforestry in Southwest Asia.

13.2 General Features of the Southwest Asia Region

The southwest Asia region extends from the mid-latitudes to the tropics and encompasses a swath of land stretching zonally from the eastern shores of the Mediterranean Sea to the Himalayan Mountains and meridionally from the Caspian Sea to the Arabian Sea (roughly 26–70°E and 12–42°N). The region covers an area of approximately 600 million ha, with a population (in 2018) of around 313 million (UN 2019). Out of the 21 countries located fully or partly within the region, 13 are a part of the Arab world. The most populous countries in Western Asia are Iran, Turkey, Iraq, Saudi Arabia and Yemen. The countries within this region include: Afghanistan, Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Jordan, Kuwait, Lebanon, Levan, Oman, Palestine, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates (UAE), and Yemen.

As per World Atlas (2022), Western Asia can be divided into four regions. (1) The southern-most region is the Arabian Peninsula. Most of the Arabian Peninsula is made up of desert terrain. The largest desert on the peninsula is the Arabian Desert, which is found in the northwest of Saudi Arabia covering a total area of 6.8 million ha, and is composed mainly of vast sand seas and sand dunes. The largest mountain range on the Arabian Peninsula is called the Sarawat, which stretches from the Saudi-Jordanian border in the north to the Gulf of Aden in the south. The center of the Arabian Peninsula is dominated by a plateau called the Najd. Lava fields dominate large parts of the western part of Saudi Arabia. The Arabian Peninsula is bordered to the west by the Red Sea and Gulf of Aqaba, to the east by the Persian Gulf and Gulf of Oman, to the south by the Gulf of Aden and the Arabian Sea, and to the north by the countries of the Fertile Crescent.

(2) As its name implies, the Fertile Crescent is a historic crescent-shaped region of fertile land that encompasses the present-day countries of Iran, Iraq, Turkey, Syria, Lebanon, Palestine, Cyprus, and Jordan. This region gave birth to some of the world's earliest civilizations, such as Mesopotamia, located in modern-day Iraq. Today, however, the Fertile Crescent is not very fertile at all, due to irrigation and dam projects that took place in the latter half of the twentieth century which diverted water away from the marshlands of the Tigris-Euphrates River systems. (3) The most northerly region of Western Asia is the Caucasus, where present-day Georgia, Armenia, and Azerbaijan are located. It is also the smallest region in Western Asia. The Caucasus countries are bordered by the Black Sea to the west, the Caspian Sea to the east, Iran to the south, and Russia to the north. The line that divides Europe and Asia runs right through the center of the Caucasus Mountains, which are the dominant geographical feature of the Caucasus region. The terrain of the Caucasus is composed of several features, including grassy highlands, snow-capped crags, coniferous and deciduous forests, shrubby plateaus, and swamp forests. (4) To the

southwest of the Caucasus is Anatolia, otherwise known as Asia Minor. Anatolia also borders Iran to the east, the Aegean Sea to the west, the Black Sea to the north, and the Fertile Crescent and Mediterranean Sea to the south. Geographically, Anatolia can be divided into four regions namely the Black Sea region dominated by mountain ranges, the Mediterranean region consisting of fertile coastal plains, the Anatolian plateau, and the Eastern Anatolia which is rugged territory with higher elevations. Mount Ararat, the tallest mountain in Turkey is located in this region giving birth to various rivers, including the northern ends of the Tigris and Euphrates rivers.

The region is endowed with diverse soils, but the land has many severe limitations. In Jordan, Syria, Lebanon, Iraq, and Palestine, the soils of the valleys are very sandy soils (e.g., Arenosols or Psamments) as well as fertile alluvial soils (e.g., Fluvisols or Fluvents). In the highlands, steppe, and desert regions, the main soil types are Calcisols (Calcids) and Cambisols (Aridisols), Arenosols (Psamments) and Leptosols (Lithic subgroups), and Vertisols which are calcareous in the subsoil horizons (FAO 2015). However, in the Arabian Peninsula and the Gulf (Oman, Kingdom of Saudi Arabia, Kuwait, Bahrain, United Arab Emirates, Yemen, Iran, and Qatar), there are alluvial soils rich in silt and desert soils, and sandy soils poor in organic carbon but in which evaporate Tertiary Formations played an important role in the formation of contemporary minerals (Abbaslou et al. 2013).

West Asia is one of the regions most affected by land degradation, as shown by increased desertification, water scarcity, reduced productivity, increased pollution and deterioration of biodiversity and ecosystems as a whole (Mirzabaev et al. 2019). Deserts and drylands occupy around two thirds of the West Asia region, including rangelands. Cultivated land makes up 4.8% and the forests 1.4% of the total area (AOAD 2014), where arable land per person in West Asia countries varies significantly from less than 0.1 ha in most Gulf Cooperation Council (GCC) countries, where the percentage of agricultural land is only 2.2% of total land area; to less than 0.3 ha per person in Syria. Moreover, agricultural production that is dependent on irrigated and rain-fed cultivation faces competition for water resources from other sectors. However, about 40% of West Asia's land area is subject to desertification, and the region is affected by severe to very severe vegetation degradation and about 6% of the region's land area is slightly desertified, 21% is moderately desertified, 31% is severely desertified, and 11% is very severely desertified (AOAD 2014). It is reported that 83% of the marginal lands of West Asia are considered to be in danger of desertification while in the Arabian Peninsula, 89.6% of the land is degraded (AOAD 2014; Abahussain et al. 2002). In addition, rangeland constitutes two thirds of the total area of the region, consisting of arid to semiarid territories (AOAD 2014). Rangeland is partially covered with grass and shrubs, while experiencing low rainfall (less than 200 mm annually), and is a source of forage for livestock and of cultural and social value for the people. The climate in southwest Asia region is varied with desert climate mostly in the Arabian Peninsula, the Levan and Iraq, semiarid areas in Turkey, Iran and Levan, Mediterranean in coastal area of Levan (Fig. 13.1).

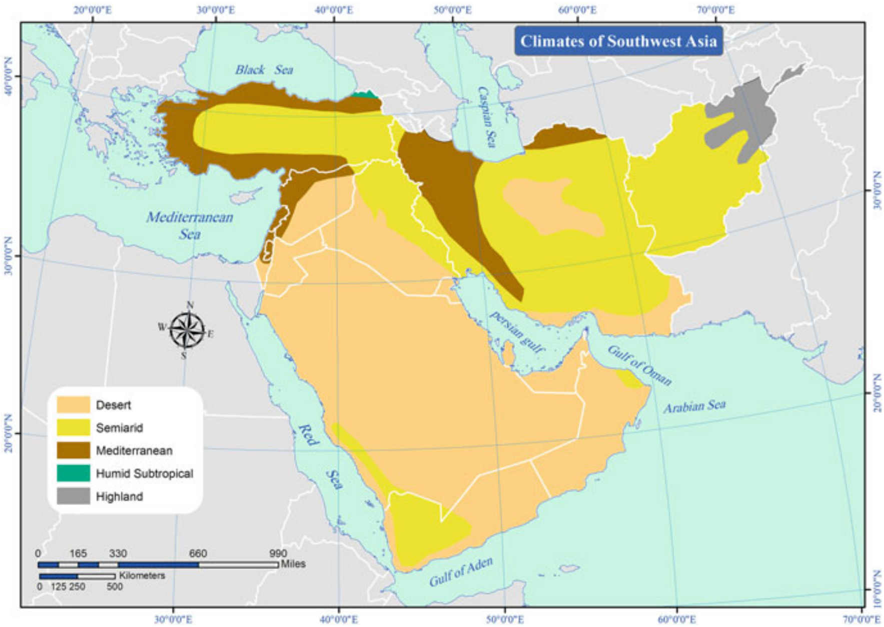

Fig. 13.1 The climate in the Southwest Asia region

The arid and semiarid climate of the region and climate change constitute major drivers affecting land, resources and humans alike, working as a determinants of land productivity. The most limiting factor for development in this region is water scarcity, which is expected to reach severe levels by 2025 (UNEP 2016). What is historically known as the Fertile Crescent—Iraq, Syria, Jordan, Lebanon, and the Occupied Palestinian Territories (OPT)—is now likely be unproductive before the end of the century, mainly because of a deteriorating supply of water from surface and groundwater sources (Tolba and Saab 2009).

Climate change is a uniquely challenging issue in the West Asia region. The region is already a part of the world that is classified as arid or hyperarid (Cherlet et al. 2018; Prăvălie 2016), and the strain that climate change will place on water resources, ecosystems, coastal zones, as well as on food security and the ability to cope with extreme weather conditions, is exacerbated by the disparity in wealth, infrastructure and human capacity to adequately deal with expected impacts (https://www.unep.org/regions/west-asia/regional-initiatives/responding-climate-change).

The West Asia Climate Change Network was launched in September 2010 in Jeddah, Kingdom of Saudi Arabia. It supersedes the Regional Adaptation Network initiated in 2009. The main purpose of the Network is to facilitate exchange of experience, information and knowledge among its members on aspects of climate change of relevance to the West Asia region including but not limited to adaptation, mitigation, technology and finance. The oil and gas sectors are the largest man-made emission sources, responsible for 24% of global anthropogenic methane emissions.

The Methane Alliance is a global initiative, conducted in partnership with the Climate and Clean Air Coalition (CCAC), to reduce the emissions of methane. The Alliance's aim is to gain commitment from oil and gas producers, including the West Asia region, to include methane emission reductions in the next round of nationally determined contributions (NDCs), a key component of the Paris Climate Agreement, targeting a 45% reduction by 2025 and 60% to 75% by 2030 (UNEP, reference as above).

The vegetation in this region is important for landraces and wild progenitors of our crops, including cereals, pulses, oil- and fiber-yielding plants, vegetables and fruits, all of which require research and protection (Zohary et al. 2012). West Asia has rich and diverse vegetation distributed in different habitats including high mountains, upland plateaus, inland, riverine and coastal plains, sand deserts and wetlands (EOAR 2010). The region also forms a center of diversification of several genera, notably in the Asteraceae (sunflower), Caryophyllaceae (pinks and carnations), and Lamiaceae (mint) families. It is a very important region for landraces and wild progenitors of our crops, including cereals, pulses, oil- and fiber-yielding plants, vegetables and fruits, all of which need research and protection (Zohary et al. 2012). Moreover, the biodiversity of the region is also threatened by mismanagement of groundwater resources, coupled with increasing surface temperatures, evaporation rates, and reduced rates of precipitation, which have led to salinization of water and soils in several countries of West Asia. The phenomena vary in extent and magnitude from one country to another, and sulphates and chlorides are the main salts increasing in the waters and soils of the region, which affect the vegetation and biodiversity in the region. The biodiversity, however, is not yet fully explored botanically. The floras of many of the countries are outdated or incomplete and very few have a red list of plant species. However, indications of the region's rich biodiversity can be found in the many wild relatives of fruit trees found in Lebanon, Jordan and Syria. These species and types have adapted to tough conditions including extremes in temperature combined with extensive drought and poor soil fertility (UNEP 2016). They are excellent resources for future research into rootstocks for, among other characteristics, dwarfism and drought or calcareous soil tolerance. Medicinal plants are widely distributed in Jordan and are massively used by local people in folk medicine as hot or cold drinks, and are chewed fresh or as dry raw materials.

Livelihoods, with around 364 million inhabitants, in the MEWA region are one of extreme heterogeneity (UNDESA 2017). Thanks to their oil wealth, the Gulf Cooperation Council (GCC) monarchies—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE)—are among the wealthiest countries of the world with a gross domestic product (GDP) per capita, purchasing power parity, ranging from USD 50526 to USD 154008. The State of Palestine, Yemen and Afghanistan, meanwhile, are among the poorest (USD 4885, 2150 and 1981, respectively). With the exception of Afghanistan and Yemen, the region is highly urbanized: 67% of its population live in cities. Jordan and the GCC countries are the most urbanized with nearly 84% of their populations living in urban settlements; Afghanistan and Yemen are the least urbanized with 27% and 35%, respectively, of their populations living in cities (UCLG and UCLG-MEWA 2019).

Historically, the region was dominated by settled agriculture and pastoral livelihoods. Indeed, it is the cradle of agriculture, where domestication of many food crops began in what is called the Fertile Crescent. In Euphrates and Tigris watershed, forests play role in the livelihood strategies of rural poor. While they are one of the sources of rural livelihoods, the benefits the poor derive from grazing, fodder, NWFPs and illicit, legal and subsidized timber and fuel wood are considerable. These forests contribute to increased income at the household level as well as a certain amount of food security and decreased vulnerability. However, despite their obvious benefits, forest management and production in this watershed are not part of household. Forests are secondary to the main production strategies which remain focused on livestock, agriculture and migration. Partly, it is because the policies and institutions of Euphrates and Tigris watershed that mediate access to forests do not provide an adequate incentive and planning framework (Kangarani 2005).

13.3 Threats to Land and Forest Resources in Southwest Asia

Forest resources in Southwest Asian countries are inadequate to satisfy the populations' needs for wood and nonwood forest products. This required efforts to find new methods of solving the economic problems related to the components of wood needs and the funds for its development generally. As large areas of forests were destroyed, burned, overgrazed and degraded by the inhabitants, a huge loss of most existing natural stands and deficiency of forest production were noticed. The major threats to the land and forests can be summarized in the following:

13.3.1 Overgrazing and Browsing

Overgrazing leads to land degradation in drylands in dry years, when the grazing loads are much higher than the pasture capacity, overgrazing is notified in the forests, which is considered as great danger for the vegetation, grass cover, shrubs and short trees; moreover, tree branches are broken, cut and pulled out of the forest by pastoralists to provide fodder for sheep, goats, camels, and cows; however in many cases with unorganized goat farming, the risk of forest deterioration is higher due to the intensive overgrazing.

13.3.2 Wooding and Charring

Despite of making charcoal and wooding is common and considered as important means of livelihood or complementary sources of income, however as threat for ecosystem it follows the grazing, and characterized as the excessive logging of some parts or the whole tree for heating or charring, leading to the deterioration of the quantity and quality of the forest.

13.3.3 Fires

Fires are a major problem that threatens the existence of forests (Fig. 13.2); however, they are considered as a natural drivers of some forest species distribution. According to an analysis conducted by the Food and Agriculture Organization (FAO 2010), fires cause more damage to forests than any of the other natural factors such as bacterial diseases, insects, hurricanes, frost, and other agents. Moreover, natural fires in addition to agricultural crop residues burning at the end of the summer time especially in the dry months of August, September, and October harm biodiversity and ecosystem destruction. In most regions of the world, the largest proportion of fires is attributed to natural causes, especially lightning strikes; however, in the Mediterranean region, the situation is totally different, where most fires are arson-related, but the natural percentage not exceeded 1–5% of the total fires in a country. Perhaps, the largest and most dangerous fires that occurred in Syria was during the year of 2020, where the number of fires in the governorates of Lattakia, Tartous, Homs, and Hama reached 2115 and 365 fires in agricultural lands and forests, respectively.

Fig. 13.2 The fire in the forest of Syria

13.3.4 Pests

Over native species the invasive and aggressive plant and insect species may gain advantage with future variations (Randhir and Erol 2013). In case of natural balance with other elements of the ecosystem, insects and diseases are considered as a major and important component of the forest ecosystems. However, the violation of this balance can expose the threat of the insects and diseases, where the most economically important insects, on the protean pine, are pine processionary (*Thaumetopoea pityocampa*), and pumice and saw wasps on oak leaves, in addition to the important diseases such as leaf-tubers on Palestinian pawpaw, oak leaf mottle, Sidr fruit fly and cedar tree wasps. Certain invasive plant species are expected to increase dramatically as their large range and tolerance of harsh conditions will allow them to rapidly move into new areas (Wallery 2012), moreover disorders can interact with changes in temperature and precipitation or with each other to increase risks to forests. For example, wildfire can make a forest more vulnerable to pests (USGCRP 2009; Backlund et al. 2008).

13.3.5 Climate Change and Its Effects

The concept of climate change and its impact include changes in average temperatures (maximum and minimum); the amount, intensity and distribution of precipitation geographically and temporally; snow melting; torrential rains; evaporation; soil moisture status; frequency of disturbances such as droughts, epidemics, insects, severe storms and forest fires; the composition of the vegetation cover; changes in atmosphere and air quality; and land use changes (CCSP 2008; Nally et al. 2008; Malmsheimer et al. 2011). Moreover, specialists indicated that the earth's climate has changed, and will continue to change with the warm wave, which have increased since eighties of last century, where the form, frequency and severity of precipitation have been changed, with probability of higher rainfall rates in some areas, while some others will suffer from drought severity and recurrence, moreover increasing the possibility of forest fires, which affects negatively the plant and animal species richness (Clarke 2007; CCSP 2008).

Additionally, some studies have shown that the atmosphere temperatures near the surface of the earth in the northern hemisphere have been increased by about 0.2–0.6 °C during the twentieth century; furthermore, some researchers have predicted that the temperature may increase between 1.4 and 5.8 °C during 2100 than that in 1990 (Kipp 2008; Trenberth 1998; IPCC 2021). It is expected that the rapid rise in of atmosphere air temperature leads to the regional and global climate change, which may have significant consequences on human and natural systems; clearest of which are reflected in the decrease of precipitation amounts, its frequency, and tendency toward drought, and the following increase of numbers and severity of fires (Ali 2008; Mckengie et al. 2004), hence impacting biodiversity, accordingly it is expected that pine forests will be the most affected by climate change (Ali 2008; Abido 2009), and 20–30% of forest plants and animals will face extinction in case of atmosphere temperature rise of 1.5–2.5 °C (Clarke 2007; Lo 2008).

Drought is a serious climatic phenomenon, which magnified the negative impact if accompanied by destructive human activities (Losey and Jurina 2003; IPCC 2001), the dominance of harsher environmental conditions in the Mediterranean region which may threaten the native forests and biodiversity (Peñuelas et al. 2004; Clarke 2007). Furthermore, it is also assumed that the main contributor to the diversity of vegetation cover composition in the Mediterranean region was recurrence of drought (Archaux and Wolters 2006); however, increase in the amount of dead wood in the forest floor leads to an increase in species that depend on dead wood for their growth, such as fungi, lichens, and algae (Archaux and Wolters 2006).

Climate change, along with pollution effects, consequences of environment overexploitation and the destruction of environmental nests, are among the direct and most negative threats to biodiversity (Rebetez et al. 2006; Archaux and Wolters 2006), moreover, climate change leads to a significant increase of high fires possibility due to temperatures rise and drought domination (Afonso Do et al. 2009) impacting biodiversity. Additionally, species change, regional shifts of vegetation cover, redistribution of plants, insects and animals, upward migration toward the pole, and the change of the rapid evolutionary adaptation ability are considered among the most important consequences of climate change (Nally et al. 2008; Kipp 2008; Peñuelas et al. 2004). Moreover, climate changes may have a long-term negative impact on biodiversity (Peñuelas et al. 2004; Archaux and Wolters 2006) as due to climate change there is also a change in the population of species, so that they become less diverse and give space to rapidly renewed harmful species (Clarke 2007). Sharp changes in climate prevent plant species developed over ages, to adapt and react effectively (Archaux and Wolters 2006), especially that of qualitative nutritional needs, limited root spread, small size and long-life cycle, which in turn are more at risk of extinction (UNEP 2010; Nally et al. 2008; Clarke 2007).

13.4 Agroforestry Systems and Their Impact on Livelihood Security

The traditional knowledge and the underlying ecological principles concerning indigenous agroforestry systems have been successfully used in designing the improved systems. Many of them such as improved fallows, home gardens, alley cropping, and park systems have been evolved as modern agroforestry systems (Dagar and Tewari 2017; Sileshi et al. 2020). During past four decades, agroforestry has come of age and begun to attract the attention of the international scientific community, primarily as a means for sustaining agricultural productivity in marginal lands and solving the second-generation problems such as secondary salinization due to waterlogging and contamination of water resources due to the use of excess nitrogen fertilizers and pesticides (some reference e.g., Dagar and Minhas 2016; Dagar and Tewari 2017; Dagar et al. 2016, 2019, 2020a, b) and Southwest Asia is no exception. Research efforts have shown that most of the degraded areas including saline, waterlogged, and perturbation ecologies like mine spoils and coastal degraded mangrove areas can be made productive by adopting suitable agroforestry techniques involving highly remunerative components such as plantation-based farming systems, high-value medicinal and aromatic plants, livestock, fishery, poultry, forest and fruit trees, and vegetables (Dagar et al. 2014). New concepts such as integrated farming systems and urban and periurban agroforestry have emerged (Borelli et al. 2017). Consequently, the knowledge base of agroforestry is being expanded at a rapid pace as illustrated by the increasing number and quality of scientific publications of various forms on different aspects of agroforestry. It is both a challenge and an opportunity to scientific community working in this interdisciplinary field. In order to prepare themselves better for facing future challenges and seizing the opportunities, scientists need access to synthesized information and develop technologies to assess the environmental benefits we get from different agroforestry services (Gupta et al. 2019). In present times, agroforestry is not only growing crops with trees and rearing livestock on grazing lands consisting of tree-component but also a problem-solving science such as restoring of degraded landscapes, creating food and fodder parks, enhancing biodiversity, lowering of water tables in waterlogged areas, and providing environmental services and mitigating climate change (Dagar et al. 2020a, b).

Generally, agroforestry systems have been classified into the following classes (Mead 2009; Nair et al. 2021): agrisilvicultural [sequential (improved fallows, taungya, relay intercropping); spatially mixed, i.e., simultaneous (parkland systems, plantation crop combinations, home gardens); spatially zoned (alley cropping, boundary planting, strip planting, i.e., plantations with corridor farming, shelterbelts, woodlots); silvopastoral systems [spatially mixed (simultaneous practices), i.e., trees on rangeland or pastures or parkland systems, perennial crops with pasture—agricultural plantations like rubber or coconut and orchards, spatially zoned (simultaneous practices) such as boundary planting, shelterbelts and wood lots]; agrosilvopastoral systems [spatially mixed (simultaneous practices) like home gardens with animals, spatially zoned (simultaneous practices) like multipurpose woody hedgerows, i.e., woody hedges for fodder, mulch, wood fuel, soil conservation etc. and multipurpose woodlots]; and other systems such as entomoforestry (trees with insects—beekeeping) and aqua forestry—trees planted around fishponds with fish utilizing fallen leaves etc., sometimes spatially mixed. In southwest Asia region also, many traditional and improved agroforestry systems are found (Table 13.1) and play important role in livelihood security and providing environmental services. Some of these successful stories have been described briefly in the following section.

Table 13.1 Traditional agroforestry systems and practices in Southwest Asia region

AF system	AF practice	Major components and important woody species	Country	Reference
Agrisilvicultural systems—Trees with crops	Spatially mixed (simultaneous practices)			
	Home gardens (multistrata systems)	Chestnuts (*Castanea sativa*) Jujube *Zizyphus lotus*)	Syria Syria and Lebanon	Nahal et al. (1989)
		Apple, cherry, walnut, peach, apricot *Juglans regia, Castanea sativa*	Turkey	Tolunay et al. (2007)
	Spatially zoned (simultaneous practices)			
	Boundary planting	Fruiting pine (*Pinus pinea*)	Syria and Lebanon	Mutke and Calama (2013)
	On agricultural land	*Populus nigra, Quercus coccifera, Elaeagnus angustifolia, Prunus* sp	Turkey	Tolunay et al. (2007)
Silvopastoral systems—Trees with pasture and/or animals	Spatially zoned (simultaneous practices)			
	Boundary planting	Carob (*Ceratonia siliqua*)	Syria	Battle and Tous (1997)
	Shelterbelts	Carob	Syria	Nahal et al. (1989)
		Populus nigra, Elaeagnus angustifolia, Cupressus sempervirens	Turkey	Tolunay et al. (2007)
		Cupressus sempervirens *Acacia cyanophylla*	Cyprus	Leontiades (1989)
	Woodlots	Euphrates poplar (*Populus euphratica*)	Syria	Nahal (2002, 2003), Chen (2001)
		Hybrid poplar, *Casuarina, Eucalyptus microtheca, E. camaldulensis.*	Iraq	en.wikipedia.org
	Silvo-pastoral	*Acacia ampliceps*	UAE	Qureshi and Ismail (2017)
		Species of *Platanus, Morus, Quercus, Pinus, Cedrus*	Turkey	Tolunay et al. (2007)
Agrosilvopastoral systems—Trees with crops and pasture/animals	Spatially zoned (simultaneous practices)			
	Multipurpose woody hedgerows/alley cropping	Mahlab (*Cerasus mahaleb*) Sumac (*Rhus coriaria*) Laurel (*Laurus nobilis*)	Syria	Nahal (2012)
		Poplars, willows, silver maple, birches	UAE	

(continued)

Table 13.1 (continued)

AF system	AF practice	Major components and important woody species	Country	Reference
				Qureshi and Ismail (2017)
		Apple, cherry, walnut, peach, apricot	Turkey	Tolunay et al. (2007)
		Poplar, olive, casuarina	Iraq	en.wikipedia.org
	Multipurpose woodlots	Mangroves, *Arthrocnemum indicum, Tamarix articulata, Acacia, Casuarina, Prosopis*	Saudi Arabia, UAE, Jordan	Qureshi and Ismail (2017), Ismail et al. (2019)
Other systems	Entomoforestry (trees with insects)—Trees and beekeeping	Christ's thorn jujube (*Ziziphus spina-christi*) *Ceratonia siliqua* *Robinia pseudoacacia*	Saudi Arabia Syria Turkey	Nahal et al. (1989), Tolunay et al. (2007)
	Reclamation of salty soils	*Robinia pseudoacacia* *Acacia cyanophylla* Halophytes	Turkey	Tolunay et al. (2007)
		Atriplex, Acacia ampliceps, Tamarix, Halophytes	UAE	Qureshi and Ismail (2017), Ismail et al. (2019)
	Land scape	*Acacia ampliceps* *Azadirachta indica* *Phoenix dactylifera*	UAE	Ismail et al. (2019)

13.4.1 Agroforestry Systems Based on Fruit Trees

In Southwest Asia, many fruit trees such as Chestnut (*Castanea sativa*), Christ's thorn jujube (*Ziziphus spina-christi*), Chinese jujube (*Z. lotus*), Carob (*Ceratonia siliqua*), Mahlab (*Cerasus mahaleb*), date (*Phoenix dactylifera*), Figs (*Ficus carica*), grapes (*Vitis vinifera*), pomegranate (*Punica granatum*), peach (*Prunus persica*), walnut (*Juglans regia*), cherry (*Prunus avium/cerasus*), apricot (*Prunus armeniaca*), and oil-yielding olives (*Olea europaea*) have long history of cultivation and play vital role in the economy of the region. Some of these are also found grown in wild as well as cultivated. Some play very important role as agroforestry tree in pastures or with crops or in isolation and are described here.

13.4.1.1 Chestnut (*Castanea sativa*)

Chestnut is a huge perennial tree, which can reach a height of 30–35 m, with erect trunk, thick skeletal branches, and the fruits (every 2–3 fruits) gather in a sepals covered with thorns called the echinococcus (Fig. 13.3). It is a multipurpose species which is cultivated for timber, nut, and tannin production, and positively contributes to the forestry landscape. From a nutritional point of view, chestnuts are characterized by low fat (20–50 g kg^{-1}) and protein (20–40 g kg^{-1}) contents but a high carbohydrate content (Barreira et al. 2009). The main nutrient in the chestnut is starch, which accounts for 60% of the dry weight (DW) and also rich in micronutrients such as vitamins, minerals and trace elements as well as bioactive compounds such as phenolics and the fat contains high amount of unsaturated fatty acids, essential fatty acids, linoleic and linolenic acids (Españaa et al. 2011).

In Syria, besides getting fruits, chestnut is cultivated in agroforestry systems to protect soils from water erosion. Its afforestation was started in the beginning of the seventies at the sites of Al-Qusayr in Homs, Jabal al-Nabi Matta in Tartous, and Barshin in Hama and Lattakia, where the area planted with chestnut trees is about 1328 ha and the planted trees number exceeded one million trees (Agricultural Statistical Group 2016). The advantages of chestnut cultivation within agroforestry projects include sustainability of natural resources preservation and the increase of national income related to the tourism investment in artificial afforestation sites; providing a job opportunity, improving the livelihood of more than 20,000 people; and provides shelter and pasture for wild animals and pasture for domestic animals such as sheep from vegetable weeds or from the leaves and fruits of the forest. The tree is commonly cultivated with rain-fed wheat, barley, corn, cotton, olives, vegetables, and more frequently on pasture lands.

Fig. 13.3 Chestnut tree in Syria

In Lebanon, chestnut cultivation began in the town of Tarshish in 1996, then distributed to the neighboring mountain villages such as Jezzine, Rayfoun, Bcharre, Baskinta, Bikfaya, Kafr Silwan, and others, where the capital of chestnuts became the village of Tarshish with total production reached 100 tons in 2020. The annual Lebanon imports of chestnut, mostly from Turkey and Italy, are around 6500 tons. The reasons of farmers switching to alternative crops, including chestnut are: the low risk of diseases and insect-infection, moreover, its resistance to various climate fluctuations; low production cost, related to no chemical application; lack of tourism and agricultural activities in the villages; and easy to harvest as farmers have only to collect and pack the spontaneously dropped mature fruits in mid-September and late October, moreover easy for marketing. The main crops are barley, potato, corn, vegetables and grapes along with sheep and goat herding on pasturelands, where this tree along with olive and other fruit trees may play an important role. Viticulture in Lebanon is considered a thriving industry nowadays and is mainly concentrated in the Beqaa Valley with wineries producing an annual amount of approximately 600,000 cases of wine.

13.4.1.2 Wild Jujube (*Ziziphus lotus*)

Jujube, of family Rhamnaceae, is a deciduous shrub reaching a height of 5 m with a grey trunk (Arndt et al. 2001) and branches with sharp spines and bisexual yellow flower (Fig. 13.4). The fruits are unicorn, mostly ripening in October. The root system, in search for moisture, might go to the depth up to 5 m. These trees have

Fig. 13.4 Jujube tree in desert pasture land

existed since ancient times in the Levant region, where they are located on the upper Jazeera region near the Tigris River, in the Salamiyah region to the east of Hama and to the south of Baniyas (Nahal et al. 1989). Jujube tree grows and distributes in a different climatic zone from tropical and subtropical to arid and semiarid regions, as it tolerates harsh conditions of drought, wind and sunlight. It is noteworthy, that the wild jujube is distinguished by its high ability to withstand extreme cold with a temperature drop of −28 °C during its dormant period in winter, and heat of up to +40 °C during the active period in summer. It prefers the sunny and well aerated areas of the south and south-east mountainous slopes. For maturity, the fruits need a long, humid and relatively hot summer with an average temperature of 30–35 °C (Makhoul and Mahfoud 2000).

Jujube fruits can be eaten as fresh, as prepared from them jams, juices and sweets (jelly), moreover, the fruits are also usually dried, which can be eaten in the same way as the dates. Furthermore, fruits have many medicinal properties, such as stimulating blood circulation and reducing cholesterol in the body as they contain quinidine and triterpenes. Hayek (1999) mentioned that the fruits contain substances that help to reduce obesity, and in the formation of collagen in the body, moreover, it is useful in resisting cancer and heart disease with its high percentage of antioxidants such as anthocyanin and vitamins C and E. Additionally, due to richness in vitamins B6, B2, and B1, it is also used in the treatment of nerve weakness and mental depression (Insomnia) as well as treatment of fever and measles (Hsu 1980). This plant is rich in polyphenols, cyclopeptide alkaloids, dammarane saponins, vitamins, minerals, amino acids, and polyunsaturated fatty acids responsible for most of the biologically relevant activities including antimicrobial, anti-inflammatory, hypoglycemic, antioxidant, and immunomodulatory effects (Abdoul-Azize 2016). The seeds contain oil of about 50% of its total weight, the oil extracted from it is called jujuba oil, which considered among the most important plant extracts used for different purposes including pharmaceutical companies to prepare some types of medicines and cosmetics. Due to the diversity of its medicinal and food uses and economic importance, it represents a distinctive type, suitable for sustainable agriculture programs.

The introduction of “jujube“within the horticultural-forest investment systems gives a wide range of benefits for the farmers. As agroforestry tree, in Syria it is cultivated mainly on pasture desertified land in many areas such as Al-Haffah, Al-Qardaha, Jableh, Safita, and Afrin in addition to some areas in Idlib and Damascus countryside, as a supplement plant to the cultivated olive trees, citrus and other fruit trees where it is planted on the edges of the fields and orchards. Such system of agroforestry is also applied in Lebanon in the villages of Manqeq Alia, Bhamdoun, Al Matn and Ain El Helzon, as well as in separate areas of Palestine, where, due to their beautiful decorative shape and benefit from the fruits, inhabitants plant the trees near their homes and also as decorative on urban landscapes.

13.4.1.3 Christ’s Thorn Jujube (*Ziziphus spina-christi*)

Christ’s thorn jujube is a fast-growing shrub, medium to large in size, spreading with huge shade, evergreen, with a height of 3–5 m (Fig. 13.5), and in some cases with

Fig. 13.5 Christ's thorn jujube tree in Saudi Arabia

suitable environmental conditions, it can reach up to 10 m (Abdullah and Mammad 2004). The fruits are small to large with multiple shapes, including spherical, oval, with the different diameters related to the variety, with 1.5–2 cm, and up to 5 cm for some varieties, the color of the fruits is green in the early stages of formation, then turns into yellow when the fruits are fully grown, then red, or reddish-brown at maturity, the taste of the fruits is astringent, moreover it is a pulp with a pseudo-fleshy shell, and inside each a single stone seed. Christ's thorn jujube is considered one of the most important and most widespread fruit trees in the Arab world, because its fruits are desirable. Honey from the hives developed on the tree is considered one of the finest mono-floral honeys in the world, with high value related to the limited availability throughout the year in addition to its special nutritional and medicinal properties, as the bees produce a red honey with distinctive medical benefits. The fruits, seeds, leaves, roots, and bark of the plant have been used in traditional medicine in Middle East (Asgarpanah and Haghighat 2012). The mineral concentration (mg per 100 g) reported by Ishag (2021) as: Ca (57.22), Mg (72.11), Na (9.12), Fe (2.81), Cu (0.34), Ni (0.25), Al (3.42), As (0.37) and Pb (0.31). He also reported the other concentrations such as sugars content, i.e., fructose (175.58 g kg^{-1}), glucose (158.34 g kg^{-1}) and sucrose (132.02 g kg^{-1}) and protein (5.38%), fiber (4.77%), fat (1.09%), and total carbohydrates (77.26%). The total results showed that the fruit pulp is very rich with sugars and nutritionally essential minerals.

The coal from the wood is used after mixing with vinegar for the treatment of snake bite, while its boiled leaves as a general tonic for the body, and it has a narcotic and laxative effect on the intestines, and as antidiarrhea, fever, and measles (Al-Obaidi 2000). The sap extracted from the bark used as an ointment to strengthen the scalp, for treatment of tumors and pimples, furthermore, its fruits and seeds for preparation of powders useful for treating liver diseases, healing wounds, relieving nervous tension, as well as ear and throat infections (Al-Obaidi 2000). For the abundance of its flowers and the beauty of its landscape, it is used as an ornamental tree, planted in natural parks, public and private gardens, and coastal areas and wood is used in the manufacture of furniture, buildings, apiaries and field tools (Minkov et al. 1968).

The tree is widely adopted as agroforestry tree in Saudi Arabia, where annually the Ministry of Agriculture in cooperation with the Ministry of Transport work to plant three million trees along the road-sides, and as landscape-tree in cities, as it needs less maintenance compared to other trees, and high ability to grow after (2–3) months from the any fire due to the large carbohydrate stock in its root, accordingly it is found abundantly around Taif Governorate, especially Isdar area in the southwestern parts of the Sarawat Mountains cities of Yemen, and also found grown in a plateau (El-Juhany and Aref 2009). Furthermore, it is found in Wadi Badan as well as and the Jordan Valley, Dead Sea area, Tubas and Deir area in Palestine and Aqaba. The tree is one of the most suitable plants used in sand dune stabilization and desertification control. It can be cultivated in high saline soil as it tolerates the salinity up to 0.9% and withstands harsh conditions of drought and high temperatures in various types of lands, including desert. The tree is part of shelter-belts, grown on pasture lands and cultivated fields as alleys with rain-fed wheat, barley, oats, vegetable crops and other commercial plantations such as olive and grapes.

13.4.1.4 Carob (*Ceratonia siliqua*)

The carob is a perennial evergreen tree or shrub (Fig. 13.6) of Caesalpiniaceae family, widely cultivated including Cyprus, Turkey and Lebanon for its edible pods and as an ornamental tree in gardens and landscapes. The carob tree an indigenous drought- and temperature-tolerant tree cultivated in Cyprus for centuries. In the past, it significantly benefited the agricultural economy of the island and was widely known as the "black gold" of Cyprus. In recent years, carob's health benefits and nutritional value are being highlighted and therefore traditional carob-based food products end up in the market. In Cyprus, many traditional carob products such as carob syrup (charoupomelo) which is exported to many countries, candies, drags, powder and cream are available. Carob fruits are characterized by high sugar content (48–56%) (mainly sucrose, glucose, and fructose), protein (3–4%), a low-fat content (0.2–0.6%), low content of alkaloids, and high content of dietary fibers, especially in the seeds and minerals (e.g., K, Ca, Mg, Na, Cu, Fe, Mn, Zn), and is free of gluten (Papaefstathiou et al. 2018). Carob powder is a valuable source of vitamins E, D, C,

Fig. 13.6 Carob tree in the fields of Syria

Niacin, B6, and folic acid; vitamins A, B2, and B12 are provided in lower levels; and powder oil is composed of 17 fatty acids, mainly oleic, linoleic, palmitic, and stearic acid at 40.45%, 23.19%, 11.01%, and 3.08%, respectively (Papaefstathiou et al. 2018).

The fruits are used in animal feeding as a valuable fodder equivalent to barley, where every 1 kg of dry fruits equivalent full feed unit (Nahal et al. 1989), moreover, carob contributes to enrich the pastures of bees with nectary flowers, especially it blooms in the Autumn (Kebely 1998). An oily substance is extracted from the seeds for the manufacture of aircraft paint, which makes it rust resistant (Arab Organization for Agricultural Development 1994), while gum obtained from the endosperm of the seed is almost odorless with white to yellowish white color, and generally not affected by acidity, salt or heat treatments and has wide uses in the food industry (El Batal et al. 2012).

According to the European protocol in the food industry, gum pods CBG (Carob Bean Gum) is fully approved as food additives of organic origin suitable for human use. Hence, it is mainly used for thickening as it substitutes eggs in the manufacture of salad cream, ketchup and baby food (Santos et al. 2005). Carob fruit powder is also used in the food industries, such as sweets and chocolate, as it contains a high percentage of natural sugar (Mariana et al. 2005). In addition, there is a possibility to mix carob pods powder with wheat flour to obtain high-quality bread in term of flavour, colour and maturity (Urdiain et al. 2004).

Since carob trees are beautiful, evergreen, and tolerate different environmental conditions, they are suitable for urban-agricultural systems to decorate roads and public gardens, purify the air from dust, and create protective barriers to reduce wind speed and noise (Battle and Tous 1997). Moreover, Nahal et al. (1989) pointed out the possibility of using carob trees, due to its large and wide crown, in agroforestry systems to create a windbreak and as a shade tree. It is useful to mention that the agroforestry systems of carob are in the form of silvopastoral, along with other fruit trees, olives, mulberry (*Morus alba*), and various crops such as barley, oats, wheat, corn, cotton, tobacco, potato, various vetches, and vegetables and also considered a traditional system spread in coastal areas where the carob is naturally grown, accordingly, this system is considered as multibeneficial (Nahal 2012). In Syria, the area planted with carob is around 777 ha and the number of trees is about 500,000 (Agricultural Statistical Group 2016). In Lebanon also, it is cultivated as agroforestry tree in a similar manner as mentioned earlier the area under carob is estimated at 700 ha planted near homes or on the outskirts of orchards as boundary or shelter belts. The annual production reaches 7400 and 700 tons of pods and seeds, respectively.

Carob is considered as one of the salt-tolerant trees, as it tolerates salinity equivalent to the concentration of NaCl up to 3% (Correia and Martin-Loucao 2005). It tolerates poor and dry lime soils, so it is recommended to be used in planting of saline coastal soils in semihumid climate floors (Nahal 2002). It may serve as shelter-belt and for reclamation of saline soils in coastal areas. Although Carob products are important natural food, medical and industrial products, with bad marketing they suffer from price fluctuations locally and globally. Farmers are advised to raise livestock and bees around carob plantation as it is a honey. Moreover, to plant fodder, cereals and legumes among the trees as carob does not require big agricultural investment.

13.4.1.5 Date (*Phoenix dactylifera*)

The date palm of family Arecaceae is cultivated for its edible sweet fruit called **dates** and is naturalized in many tropical and subtropical regions worldwide. It has been cultivated in the Middle East for thousands of years and there is archaeological evidence of its cultivation in Arabia from the sixth millennium BCE (https://en.wikipedia.org/wiki/Date_palm). In 2019, world production of dates was nine million tons, led by Egypt, Saudi Arabia, Iran, and Algeria with 61% of the world total combined (FAOSTAT 2019). As per USDA Food data, the fruits are rich in carbohydrates (75%), proteins (2.4%), sugar (63%), dietary fiber (8%), and energy (1180 kJ per 100 gm); and mineral contents (mg per 100 gm) are reported to be Ca, Fe, Mg, P, K, Na, and Zn to be 39, 1.02, 43, 62, 43, 62, 656, 2, and 0.3 mg, respectively (www.fao.org/faostat/en/#data/QC). In Saudi Arabia, in the year 2011, the total number of palms exceeded 3.7 million on an area of more than 170,000 ha with an annual average production of 1.07 million tons (FAO 2011). The palm is being cultivated in most of the arid regions of West Asia in isolation or as land scape trees or along with forages and arable crops.

Allbed et al. (2017) used two global climate models (GCMs), CSIRO-Mk3·0 and MIROC-H under the A2 emission scenario for 2050 and 2100, to assess the impacts of climate change. A sensitivity analysis was conducted to identify which model parameters had the most effect on date palm distribution. Further refinements of the potential distributions were performed through the integration of six nonclimatic parameters in a geographic information system. Areas containing suitable soil taxonomy, soil texture, soil salinity, land use, landform and slopes of $<7°$ for date palm were selected as suitable refining variables in order to achieve more realistic observations. The results from both GCMs exhibited a significant reduction in climatic suitability for date palm cultivation in Saudi Arabia by 2100. Climate sensitivity analysis indicated that the lower optimal soil moisture, cold stress temperature threshold and wet stress threshold parameters had the most effect on sensitivity, while other parameters were moderately sensitive or insensitive to change. They also concluded that the date palm being a sensitive to rise in temperature may not be suitable in long-run. The study also demonstrated that the inclusion of nonclimatic parameters with CLIMEX outputs increased the explanatory power of the models. Such models can provide early warning scenarios for how environmental managers should respond to changes in the distribution of the date palm in Saudi Arabia.

13.4.1.6 Mahlab (*Prunus mahaleb* syn. *Cerasus mahaleb*)

Mahlab, belonging to Rosaceae family, is a large deciduous tree reaching a height of about 15 m, with a dense spherical crown, its branches are slightly obtuse, dark brown in color (Fig. 13.7). It is a tree native to the Mediterranean area, producing highly pigmented small-stone fruits currently not used for fresh consumption due to their astringent and sour taste. The fruits are small of 1 cm in diameter, half juicy, varying in color from yellow to red then black at maturity and not suitable for fresh consumption. There is an increasing consumer and retailer demand for new natural colorants. Anthocyanins are a class of molecules already used as water-soluble natural colorant and for their health effects. Gerardi et al. (2015) reported high content of anthocyanins, flavonols, and coumarin and a strong antioxidant capacity in the fruits of *P. mahaleb* showing its economic importance.

Mahlab usually grows in high areas up to 1500 m above sea level, on mountain slopes, in river reefs and in the sunny parts of forests with limestone soils, it tolerates soil drought, winter but not spring frosts, where the static buds can withstand temperature drops up to −24 °C. In Syria, due to the high fruit prices the farmers started to plant the tree on the outskirts of their orchards as boundary plantations as well as on their farm in wider rows as alley crops. The cultivated area of mahlab is around 3339 ha with tree density of about one million (Agricultural Statistical Group

Fig. 13.7 Mahlab trees in landscapes of Syria

2016). The agroforest system in Idlib governorate includes mahlab tree, olive and cherry trees and cereal crops such as barley or corn and also on pasture lands. The system was common in particular provinces of Jericho and Jabal al-Zawiya, later its cultivation is distributed to most of the Syrian cities such as Lattakia, Tartous, Homs, Hama, Damascus countryside, Quneitra and As-Suwayda. Often the fruits are collected in the months of May and June, while it is preferable to pick the fruit of Mahlab, of green color, as the delay in picking could lead to the change into red color of lower price. Nahal (2012) indicated the benefits of using the tree in agroforestry systems as the tree possesses fragrant and beautiful white flowers, so its planting in gardens as an ornamental tree can increase economic importance and also promotes honey bee rearing for quality honey. The wood is of distinctive characteristics and used in antiques manufacture, furniture tools and musical instruments. The tree is used for grafting cherries, peach and apricots. The liquor extracted from the leaves, as well as its fruits, is an essential component of some perfumes and medicines.

13.4.2 Agroforestry Systems Based on Seed or Leaf: Spice of Commercial Importance

13.4.2.1 Sumac (*Rhus coriaria*)

Sumac, a member of family Anacardiaceae, is a shrub naturally growing in Western Asia. Its stem is 1–5 m long, strong, and woody with light reddish-brown or dark blackish, straight or slightly crooked, and crowned with a bundle of branches

Fig. 13.8 Sumac tree in Syria

(Fig. 13.8), which at the beginning of its formation are soft and reddish-green, then harden and woody, and in turn branch into thin branches. Blooming period of Sumac is from May to June. The small drupes are sun-dried and ground producing the reddish commonly known sumac powder spice.

The majority of studies conducted on Sumac have shown many potential compounds that have a substantial role in the food industry as well as in homeopathic therapy. From the retardation of oxidative processes to the treatment of fungal and bacterial infections and many more, these compounds are of great importance in improving human health and economy. Sakhr and El Khatib (2020) have reviewed physiochemical properties, medicinal, nutritional and industrial applications of Lebanese Sumac. Its antibacterial, antifungal and antioxidant properties make it a great and versatile tool to be used in the food industry, where it can be used as an efficient food preservative and natural, harmless food additive. Ripe fruits have 4.7% protein content, 18.7% fat content, 14.6% fiber content, 71.2% carbohydrate, and 100 g of sumac fruit contains 147.8 kcal (Raodh et al. 2014).

The tree planted in agroforest farming is found in many countries, such as Syria, Palestine, and Jordan. In Syria, it is found in Qalamoun, Jabal Al Arab, Idlib, and Quneitra regions, covering an area of 1146 ha with about 820,000 trees (Agricultural Statistical Group 2016). While in Palestine, it is found in the mountains of Ramallah, among olive trees and grapevines, as well as in coniferous hills and forests; however, in Jordan, it is observed as wild form in the mountains of Jerash, Ajloun, Salt, and Tafileh; moreover, due to the variety of its use, high prices, and the wide demand for it, people have started to cultivate on the outskirts of orchards. Nahal (2012) reported that the tree starts bearing fruits at the age of 3 years, with initial production around five tons per hectare, which gradually increases with the growing age, average number of trees per hectare is 2000 shrubs, where average shrub bearing is 25 kg, with a price of 10$ per kilogram of untreated sumac seeds. Sumac cultivation in agroforestry system has many advantages as it is drought tolerant, survival percentage very high, ornamental suitable for public gardens and can be used as windbreaks and also suitable for pasture lands.

13.4.2.2 Bay Laurel (*Laurus nobilis*)

Bay Laurel (family Lauraceae) is aromatic evergreen tree or large shrub (7–15 m) with green, glabrous smooth leaves, native to the Mediterranean region and is used as bay leaf for seasoning in cooking. It grows mainly in humid and semihumid environments and in light to medium brown mountainous lands. Laurel is considered one of the most important trees cultivated in the cities of Nablus, Hebron, Ramallah and Bethlehem in Palestine, moreover in Lebanon, in the regions of Hula and Wadi al-Saluki, as well as in Syria, as an ornamental tree. In Syria, it has been cultivated on an area of 2145 ha with about 1.5 million trees (Agricultural Statistical Group 2016). The most important uses of laurel are summarized by Nahal (2012). It has medicinal value and mainly used to treat respiratory and digestive disorders, soothe joint pain, as stomach tonic, appetite stimulant, and for secretion of digestive juices, in addition to the ability to induce the start of menstruation, as well as in the treatment of many skin diseases and stings of some insects such as bees, wasps, mosquitoes, bedbugs and widely used in veterinary medicine. The leaves are used for cooking, as they stimulate digestion and absorption of food, as well as help to break up heavy food such as meat. Moreover, they are used to flavor food as a spice for preserved and cooked meat and fish to improve the taste and extend the life. The leaves contain an essential oil (Ayben et al. 2004), used in ointments and soap preparation as a disinfectant for the skin, where the laurel soap industry provides many opportunities to work outside the areas of laurel cultivation for example in Syria this industry is concentrated in Kasab region and Aleppo, with more than 60 factories for the manufacture of laurel soap. It is tolerant to drought and extreme cold and is suitable species for agroforestry as block plantations, to control erosion of the hill-slopes, as wind breaks and also boundary plantation of arable crops such as wheat, barley, oats, cotton and vegetables. It is also found grown with other tree crops such as olive and vines.

13.4.3 Agroforestry Involving Fast-Growing Multipurpose Trees

13.4.3.1 Systems Based on Euphrates Poplar (*Populus euphratica*)

Poplar-based agroforestry (mostly as woodlots and wind breaks) is more prominent on the banks of rivers, especially in Syria on the Euphrates basin (Fig. 13.9) and its timber is the major source of fuel and home roof making. Now a days, the area of

Fig. 13.9 *Populus euphratica* stand for fuel production in Syria

Euphrates poplar in Syria is around 2346 ha, with 2.4 million trees (Agricultural Statistical Group 2016), distributed on the banks of the Khabur and Euphrates in the Jazira moreover, on the banks of Yarmouk and Hemah in southern Syria at important sites such as Hawija (isolated inland in the river in Arabic) Ayyash, Hawija Abu Hardoub, Ayyash, Al Mariya, Al Muhaid, Al Mayadin, and Al-Tabani in addition to Jarablus area in Aleppo countryside. It is necessary to point out that as an essential source of income and livelihood enhancement, hundreds of families adjacent to the Euphrates River villages depend on this type of agroforestry agriculture. Each hectare can be planted with up to 10,000 trees as woodlots, and needs to be under care for a period of at least 7 years before harvesting.

Euphrates poplar considered tolerant to salinity and dry weather, as it can be a main source of wood production in saline soils in dry countries where it is difficult to plant other trees (Nahal 2002, 2003). Poplar agroforestry provides many benefits, such as wood of medium density of up to 0.48 g cm^{-3} can be used in pulp industry; moreover, its branches are used to clean teeth, as well as in carpentry, upholstery, and panels; furthermore, it is also used in the manufacturing of boxes, containers, light tools, sulfur, paper pulp, and their derivatives in addition to stabilizing the marginal floodplain soils on the banks of the river, as well as protecting them from winds of sandstorms and the damages of soil erosion. Poplars are very fast-growing and surprisingly resilient, so it is an ideal solution for supporting animal husbandry, fish farming, tree planting and gardening activities in general. Arable crops such as wheat, barley, oats, cotton and vegetables in additions to legumes fodder crops can be cultivated as intercrops. The tree may also be planted as boundary plantation of cultivated fields. It has multiple uses such as the construction of wooden roofs, dwellings, shading, and crop protection, in addition to being a viable source of vital energy. There is no doubt that the involvement of local small farmers in new activities to generate income, so it is one of main tools for livelihood improvement.

13.4.3.2 Fruiting/Stone Pine (*Pinus pinea*)

The stone pine is a coniferous evergreen tree of family Pinaceae that can exceed 25 m in height, but 12–20 m is more typical forming an umbrella like canopy (Fig. 13.10) on a thick trunk, and, in maturity, a broad and flat crown over 8 m in width and the bark is thick, red-brown and deeply fissured into broad vertical plate (https://en.wikipedia.org/wiki/Stone_pine). The tree is native to the Mediterranean region, commonly found distributed in the Palestinian Territories, Lebanon and Syria. It is cultivated for their edible nuts since prehistoric times and now as an ornamental tree in landscapes. Other products of economic value include resin, bark for tannin extraction, and empty pine cone shells for fuel. The tree is also currently widely cultivated around the Mediterranean for environmental protection such as consolidation of coastal dunes, soil conservation and protection of coastal agricultural crops (Fady et al. 2004).

In Syria, the cultivated area of fruit pine is reported to be around 46,000 ha, and the number of trees is 32 million (Agricultural Statistical Group 2016). The most important sites of Fruit pine are in Lattakia (Al-Khuraybat, Mardian, Fido, and Beit Jabro Forests) in Tartous (Nabi Matta and Al-Sourani forest), in Homs the site of Dahr al-Qusayr, and in Quneitra the site of the Fawar spring. The fruiting pine is resilient to environmental requirements; furthermore, it is friendly to light and heat and tolerates relatively dry lands, prefers humid and semihumid bioclimatic floors, can live in the semidry floor, and tolerates dry and quarried lands, however, susceptible to soil salinity. It is used for decoration and fixing beach sand dunes, the most important use is in human food, as the yield of 1 ha averagely around 200 kg of seed pulp, moreover its oil has importance in perfumes.

Pine wood is characterized by its hardness and resistance and considered as one of the most important types for many industries such as furniture, musical instruments

Fig. 13.10 Fruiting pine in Syria and Lebanon

and etc. The pine nut, the edible kernel of the Mediterranean Stone pine is one of the world's most expensive nuts. The Iberian Peninsula accounts for about 75% of the stone pine area in the world, Portugal being the main pine producer, followed by Spain, Turkey, Lebanon, and Italy (Mutke and Calama 2013). In Lebanon, the fruiting pine has been a symbolic tree for hundreds of years, and it constitutes one of the most important types of forest trees, extending over about 113,000 ha, or about 10% of the total forest cover in Lebanon. The most prominent pine forests are located in the upper part of the slopes toward the sea in Lebanon Mountain in the districts of Matn, Baabda, and Aley. Also, most of the pine forests in this region are private property, mostly located within very small holdings; however, the forests in Jezzine district are municipal properties for its beautiful shape and natural location as a source of recreation and firewood.

The fruiting pine is very important to the local community due to the traditional goal of seed production, as pine seeds are among the most important nonwood forest products and they can provide high economic returns; furthermore, it contributes to the enhancement of the economy and local wealth as it constitutes as a highly productive system, where pine seeds production in Lebanon is 800 tons per year, with price of 26–33$ per kilogram, and considering that around 50,000 of Lebanese families depend on pine trees to provide a source of income, additionally nonwood forest products include some types of medicinal and aromatic plants and thyme. These products, unlike pine seeds, are collected by the local community for domestic use (such as cooking), in addition to the eco-tourism which considered as a main source of income for the population adjacent to the pine forests. The trees are grown on pasture lands, as boundary plantations, as wind breaks and alleys having field crops such as barley, oats, corn, vegetables and with other fruit trees.

13.4.4 Some Site-Specific Agroforestry Systems

13.4.4.1 Agroforestry Systems in Turkey

Based on earlier studies and their own, Toluney et al. (2007) reported the traditional systems found in Turkey. Under agrisilvicultural systems [alley cropping practices where fruit trees such as apple, cherry and walnut are used as alley trees and corn and various types of vegetables are used in the spatial intervals as agricultural crops in higher altitude basin areas where irrigation is not possible and dry farming (where crops such as wheat, barley, oats, etc., are grown) is implemented. Among woody tree species used are poplar, willow, oleaster, almond, etc. The trees grown in such kind of lands provide wood for fuel and building material, various shelled fruits, border specification and shade]; homegardens [involving fruit trees and vegetable plants for meeting the nutritional needs of the residents; the woody species are used for providing the other needs and various ornamental plants for aesthetic purposes; and seasonal vegetables geared towards nutritional purposes]; trees for soil conservation and reclamation [e.g., *Robinia pseudoacacia, Acacia cyanophylla* and deeprooted bushes, offering multiple uses as well as fruit trees are grown widely in upper basins in areas vulnerable to soil erosion]; and shelterbelts and wind breaks [in the flat plateau terrains of the country, Italian poplar (*Populus nigra* var. *pyramidalis*) and along the edges of agricultural terrains in the coastal areas oleaster (*Elaeagnus angustifolia* var. *orientalis*), True Cypress (*Cupressus sempervirens*) are widely used].

In silvopastoral systems, the important trees on pasture land planted include tree species such as sycamore (*Platanus occidentalis*), poplar and mulberry (*Morus alba*). These trees provide shade to the animals (mainly goats and sheep). Fodder leaf utilization is a kind of substation for animal breeding in Southeastern Anatolia of Turkey. Some species that can be used for this purpose include species of *Platanus, Morus* and *Quercus.* Animal husbandry is widespread in the upper plains of the country. In particular, all areas where the vegetation consists of Mediterranean oak (*Quercus coccifera*) and Holm oak (*Q. ilex*) are feeding grounds for the woolly goats. In protein bank system, in areas with irrigable flat plateau terrains, alfalfa (*Medicago sativa*) is grown on a rotational basis. In addition, there are production methods where corn (*Zea mays*), common oat (*Avena sativa*), garden vetch (*Vicia sativa*), *Trifolium repens, T. patens, Medicago sativa*, etc. are cultivated. This production technique also includes cattle and goat and sheep livestock raised for their meat and milk. Furthermore, alfalfa, clover, garden vetch and some corn varieties are dried for using as animal feed during winter. Grazing of cattle and goat and sheep livestock on plantation land is also quite common. Brutian pine (*Pinus brutia*), Anatolian black pine (*Pinus nigra* subsp. *pallasiana*), and Taurus cedar (*Cedrus libani*) are widespread used for afforestation in the country.

Some other important trees grown in different agroforestry systems in Turkey include *Juglans regia, Fraxinus excelsior, Populus alba, P. usbekistanica, Salix alba, S. caprea, S. babylonica, Alnus glutinosa, Melissa officinalis, Laurus nobilis, Pinus brutia, Castanea sativa, Amygdalus communis, Olea europaea, Rhus coriaria, R. ideans, Alnus orientalis, Ceratonia siliqua, Ailanthus glandulosa, Quercus ithaburensis,* and *Pistacia lentiscus* (https://www.academia.edu/30891932/Agroforestry_Policies and Raising Money for_Rural _People _in_Turkey?email_work_card=reading-history). These trees are commonly grown with field crops such as barley (Fig. 13.11) and other crops including oil crops. The animals such as sheep feed on the stubbles after harvest of the crops.

In the forested areas, it is possible to start animal grazing 10–15 years following the planting of trees. Under agrosilvopastoral systems the combinations of crops, pastures, trees and/or animals; woody hedgerows; apiculture with trees (*Pinus brutia* and *Robinia pseudoacacia* groves are preferred for keeping bee-hives), aquaforestry (along creeks, river-side, lakes, etc.) and multipurpose woodlots are common practices. Agroforestry is being given due attention in the country, particularly toward village sites.

Fig. 13.11 Some agroforestry systems in Turkey. (Photo by: TA Altunel and SE Bugday)

13.4.4.2 Agroforestry Experiences in Saudi Arabia

Saudi Arabia experiences only average annual rainfall of maximum 100 mm. Still, its agriculture is focused on the exports of date, dairy products, eggs, fish, poultry, fruits, vegetables, and flowers. In 2018, Saudi Arabia produced 1.3 million tons of date, 634,000 tons of watermelon, 624,000 tons of barley, 586,000 tons of wheat, 482,000 tons of potato, 312 tons of tomato, 144,000 tons of sorghum, and 115,000 tons of cucumber (Arab News 2021). As parts of its campaign to plant one million trees, Al-Ahsa municipality plans to double Al-Amana agricultural nursery to increase the production of seedlings of different tree species to 3.5 million. As a result of strong political will and better management of resources, the traditional nomadic pastoralism has declined and the project of Al-Baydha in Western Saudi Arabia, comprising of nine villages inside of roughly 700 km, with Beduin (tribes) inhabitants has been a success story. In 2012, a project with the aim of restoring sustainable agriculture in the area was initiated by the workers of Stanford University and Harvard University building rock terraces, check dams, and opening swales (wide, shallow ditches) in the area to harvest the rainwater. By 2015, about 4000 drought tolerant trees of ten species were planted but most of the species did not survive but in late 2018 and in 2019 rainfall occurred and the landscape sprouted new life and there is now lush green vegetative cover. Plants now thriving in Al-Baydha include fruits and nut trees, vines, culinary and medicinal herbs, ground cover with natural species, grasses, clumping plants such as ginger, turmeric, trees, shrubs, and cash crops such as frankincense and moringa (Greenprophet 2020). The project is a proven success and a lesson to learn for others. Major crops cultivated in isolation and agroforestry mode include fruits (date-palm, citrus, peach, and grapes), cereals (wheat, sorghum, barley and millet), vegetables (tomato, watermelon, egg-plant, potato, cucumber and onions), and forage crops, mainly alfalfa (https://www.fao.org/3/v9978e/v9978e0k.htm). Important trees include species of *Acacia, Ficus, Phoenix, Commiphora, Cordia, Rhus, Prosopis, Grewia, Celtis africana*, and *Balanites aegyptiaca*. Although tree species are widely distributed in the south western regions, only a few of them are forming into communities of which, *Juniperus* spp., *Olea europaea, Acacia seyal, Maerua crassifolia, Ziziphus spina-christi, Tarchonanthus camphoratus,* etc. are dominant and grow luxuriously in many parts of the Hijaz mountains. Species of *Acacia* are the most dominant tree species in Saudi Arabia and elsewhere in the Arabian Peninsula (http://www.plantdiversityofsaudiarabia.info/).

13.4.4.3 Agroforestry Evidence in Cyprus

Various forms of agroforestry have been practiced in Cyprus since time immemorial and many of them continue to be practiced to the present day. Leontiades (1989) gave a brief account of important traditional practices being followed in Cyprus. Carob and Olive trees are indigenous and found grown naturally, hence most of the farmers retain them in their cropping fields cultivated with wheat, barley, oats, corn, various vetches and leguminous crops which they cultivate annually. They harvest green forages and feed animals in stalls (cut-and-carry system) and also make hay. The stubble left in the field provides good grazing material in late summer and early autumn. A very intensive and very productive system of this form of agroforestry is practiced when there is water available for irrigation. The extensive use of fertilizers also brings about increased production under this system. However, when water is available, the tree used is no longer carob and olive but mainly citrus, which is more profitable. The under-crops, if they exist at all, are not cereals and legumes for animal food, but strawberries, peanuts, beans, carrots and other vegetables that bring in high cash returns to the farmer.

Summer temperatures in the flat, fertile plains of Cyprus may rise as high as 40 °C during the hot dry season from June through August. Under such conditions, the presence of trees with a large, dense canopy to provide shade for the farmer and his animals becomes invaluable. The traditional trees used for shade are carob, mulberry (*Morus alba)*, Persian lilac (*Melia azedarach*), oak (*Quercus lusitanica*) eucalyptus of various species, wattle (*Acacia cyanophylla*), and pines and fig trees (*Ficus carica*). The trees most commonly used as windbreaks are cypress (*Cupressus sempervirens)*, various species of *Eucalyptus, Casuarina, Tamarix*, the wattle tree (*Acacia cyanophylla*) and, to a lesser degree, pines. The planting is usually done in two rows along the boundary of the holding and the trees are staggered in the two rows. The planting distance between the trees varies from 0.5 to 2.0 m depending on species and on the degree of protection required.

13.4.4.4 Agroforestry Experience in United Arab Emirates

Dryland salinity and occurrence of highly saline groundwater are recognized as the major bottlenecks for the agricultural development in the marginal desert environment. In the United Arab Emirates (UAE), about 34% area is affected by salinity and the coastal sabkha areas are highly salinized (28.8 dS m^{-1}), whereas in the coastal regions of the Abu Dhabi Emirate, salinity is more than 200 dS m^{-1} (Qureshi and

Ismail 2017). Rising sea levels along with the over-exploitation of fresh water resources also causes seawater intrusion in coastal zones. In the hyperarid environment of UAE, integrating salt-tolerant trees and shrubs with other farm enterprises in agroforestry mode could be a useful strategy to increase the productivity. Qureshi and Ismail (2017) and Ismail et al. (2019) have given an account of some practices adopted in UAE in biosaline agroforestry. It has been found that *Acacia ampliceps* can fix nitrogen under different salinity levels ranging from 10 to 30 dS m^{-1}, thus supporting the nutrient requirements for two forage grasses *Sporobolus arabicus* and *Paspalum vaginatum*. The average yield of these grasses varied from 22 to 28 Mg dry matter per ha per year. Besides these grasses many species of *Atriplex* have been found suitable for silvopastoral system. In total, 76 halophyte species have been identified for UAE (14 sea-water tolerant, 21 halophytes for inland cultivation, 31 as semihalophytes and 2 thriving on roots of plants of Chenopodiaceae and Zygophyllaceae.

Woody trees which are found suitable for growing on pasture land or as landscape trees or in alleys include *Prosopis cineraria*, *P. juliflora, Tamarix aphylla, Salvadora persica, Phoenix dactylifera, Calligonum comosum, Azadirachta indica,* and *Acacia ampliceps*. Among mangroves *Avicennia marina* is most tolerant to biotic stress and is widely grown in coastal areas. Species of *Atriplex, Suaeda, Arthrocnemum, Salsola, Halopeplis, Halocnemum, Zygophyllum, Heliotropium, Limonium, Halopyrum, Haloxylon, Sporobolus, Paspalum, Distichlis, Sesuvium, Aeluropus,* and *Chloris* are high salt-tolerant forages, which can be cultivated irrigating with high saline waters. Among vegetable crops *Amaranthus* spp., cluster bean, *Asparagus, Chenopodium album,* and *Brassica* greens; field crops pearl millet (*Pennisetum typhoides*), barley (*Hordeum vulgare*), safflower (*Carthamus tinctorius*), oats (*Avena sativa*), Quinoa (*Chenopodium quinoa*), Desert gourd (*Citrullus colocynthis*), castor (*Ricinus communis*), and saltwort (*Salicornia bigelovii*) are important.

13.4.4.5 Agroforestry Systems Based on Mangroves

Mangrove forests distribute on the muddy coasts, as on the coasts of the Red Sea in Jordan, Saudi Arabia, the Indian Ocean coasts in Yemen and the Arabian Sea of the in Oman and the United Arab Emirates. It is likely that the mangroves have grown there since historical times (Tengberg 2002). The mangroves are growing naturally along the Red Sea coast in Saudi Arabia in 104 sites with a total area of 3452 ha (PERSGA 2015). Mangrove forests cover thousands of hectares along the shores of the United Arab Emirates and cover a large area of Abu Dhabi, which represents more than 75% of the total area of mangroves in the United Arab Emirates. Mangroves are considered as highly productive ecosystems for marine fish and shellfish as they formulate important spawning, nurturing and feeding sites, furthermore, over the decades a large number of mangroves have been removed by local people for agriculture, salt pond construction and aquaculture moreover making building materials. The economic losses due to biodiversity degradation vary from country to country in the region, where the degradation is linked either to coastal development, to land-use conversion and mining, or to low investment in habitat conservation. In Bahrain, for example, in 2015 the risk of losses in wetlands was associated with annual losses in the level of social welfare amounting to 865,000 US $ (CBD 2015). Mangroves also protect beaches from erosion, storms and sea-level rise, and play a major role in promoting biodiversity, and providing coastal communities with fish and food. Because of the importance of the mangroves, the Environment Agency in Abu Dhabi has started large-scale planting programs to rehabilitate the affected areas by the massive development in Saadiyat Island, considered as environmental cultural center in Abu Dhabi, where to mitigate the environmental damage caused on it about one million mangrove trees have been planted. Another method used by mangroves to sequester carbon dioxide in seawater is to dissolve limestone (calcium carbonate) and thus form effective carbon sinks. Aquaculture keeping mangroves intact is ideal multienterprise.

13.5 Evidence for Environmental Services

13.5.1 Biodiversity Maintenance

In West Asia, two biodiversity hotspots, the Caucasus region and the Irano-Anatolian region, exist. The biodiversity hotspot of Caucasus region is between the Caspian Sea and the Black Sea, and it overlaps six different countries which include Turkey, Russia, Iran, Georgia, Azerbaijan, and Armenia. The Caucasus Mountains are located in this region, and a section of the Greater Caucasus Mountain range separates the eastern part of Europe from the western territories of Asia. The region provides habitat to nearly 6400 species of plants with 1600 being endemic (https://www.worldatlas.com/articles/the-biodiversity-hotspots-found-in-west-asia.html). Various mammals make their home in the region including the bison and Persian leopards. Several bird species such as the hooded crow as well as the golden eagle are found within this region. The region is one of the most threatened biological hotspots in the world mainly due to the threat of illegal logging. Therefore, agroforestry may play a vital role in this region. Ministerial Roundtable on Forest Landscape Restoration of the region countries and the Bonn Challenge in the Caucasus and Central Asia that took place in June 2018 in Astana, Kazakhstan, and committed to restore over 2.5 million ha of forest degraded landscapes by 2030 mainly through afforestation and agroforestry (FAO 2019). There lies opportunity to reclaim salt-affected lands by planting species such *as Elaeagnus angustifolia, Ulmus pumila, Populus euphratica,* and *Haloxylon aphyllum* on degraded lands and pastures. Over time, these new stands could offer income opportunities for rural communities from fuelwood and, possibly, timber. In the dry bed of the Aral Sea, the plantations reduce wind erosion of salt-laden soils. Agroforestry offers opportunities to expand forest landscapes outside traditional forest areas. Windbreaks, for instance, could add to wood resources even where land is farmed intensively or is densely populated (Worbes et al. 2006). Windbreaks may also help to increase crop yields and educe agricultural water consumption (Thevs et al. 2017). Fast growing trees, especially poplars, as well as elm and mulberry are the main components of windbreaks. In Armenia, the target under tree cover has been fixed to increase from 11% to 20% through agroforestry by increasing tree-cover in 267,000 ha by 2050 and protect the biodiversity (Ministry of Environment Protection of Georgia 2015).

The Irano-Anatolian region stretches across seven nations, which include parts of Turkmenistan, Iraq, Turkey, Georgia, Iran, Azerbaijan, and Armenia. Several ecoregions are found within its range. A wide range of plant species are found within the area including 400 plant species whose distribution is mainly limited to the Anatolian Diagonal. The region has some of the world's unique plant species such as the halophytes found in Anatolia and Iran. The section of the region located in Turkey has a variety of orchids endemic to the country most of which are classified as threatened. Besides the plants, the Irano-Anatolian region is also home to a unique collection of bird species. Many birds that are considered threatened or endangered breed in the Irano-Anatolian region such as the white-headed duck and the great bustard. The area is also home to around 140 species of mammals including 10 of which that are endemic to the region. The Asiatic Cheetah (*Acinonyx jubatus venaticus*) is one of the most critically endangered mammals within this region. The region faces a significant threat from deforestation which limits the habitat available for a variety of species. In Georgia, increase in plantation cover from 0.52 to 1.3 million ha is planned to be regenerated or planted in agroforestry mode with suitable species such as evergreen species like *Rhododendron ponticum* and *Ilex colchica* in lowlands along the coast of the Black Sea and beech (*Fagus orientalis*), Caucasian fir (*Abies nordmanniana*), and oriental spruce *(Picea orientalis*) on high lands and pastures thereon, which is bound to conserve biodiversity (Ministry of Environment Protection of Georgia 2015). A study, conducted by Naser in Bahrain in 2014, analyzed the valued ecosystem components in the Arabian Gulf, which hosts some of the world's most critically endangered species, such as dugongs, green and hawksbill turtles, and supports a variety of marine ecosystems, including seagrass beds, mangroves, coral reefs and mudflats that are uniquely adapted to the environmental extremes of the region (Naser 2014). These unique biological features in the Gulf region call for concerted action to mobilize regional support at the highest levels to safeguard these vulnerable ecosystems.

Agroforestry, thus, will increase biodiversity in food production systems of any region, including soil microbial diversity (FAO 2017). Many indigenous communities (mainly tribes) of this region manage agroforestry systems using indigenous techniques that include residue management and ash deposition, enhancing nutrient recycling and conservation, and maintaining high species diversity, all of which promote agroecosystem sustainability. They know appropriate tree species and their management. They also have the knowledge necessary for the application of best nutrient management practices such as proper pruning, addition of ash to soil, composting, vermiculture, and others (Montagnini and Jordan 2005; Montagnini 2006).

13.5.2 Carbon Sequestration

Agroforestry systems (AFS) can serve an important role in climate change mitigation, due to carbon sequestration in woody components of the systems, as well as in soils. AFS can assist farmers as they seek to adapt to climate change due to the ameliorating effects of trees on local air temperatures (Montagnini and Nair 2004; Roshetko et al. 2007; Verchot et al. 2007; Murgueitio et al. 2011). Agroforestry systems in the region of Southwest Asia play crucial role in carbon sequestration as there are a wide diversity of plant species which provide an appropriate environment for that, such as agricultural afforestation activities with Euphrates poplar and other species described above. In addition, the mangrove provide habitats for different commercially important fish, turtles, shrimp, birds and invertebrates, as well as storing carbon naturally over thousands of years and mitigating the effects of climate change are among the essential environmental benefits of this system, despite of the habitat restoration initiatives, as an attempt to increase in mangrove areas in the southern Arabian Gulf, the forest ecosystems of these trees along the coasts of the Arabian Peninsula are still decreasing and fragmented, where around 40% of the mangrove area has been lost along the coasts during the past few decades, and estimated losses observed in the wet areas ranging between 0.1% and 29%, the highest loss is recorded in Jordan but the lowest in the United Arab Emirates, which both of them are considered among the highest rates in terms of risk (CBD 2015). It worth to mention, that mangroves as different trees absorb carbon dioxide from the atmosphere and isolate it at a rate exceeding 30 times more than the forests of northern, tropical, and temperate regions; however, the mangroves have a distinguishing ability to bury carbon dioxide of trapped, microalgae, and other dead organic matter, within their aerial roots forming rich sediment layers, and due to the lack of oxygen in the mangrove soil the carbon composed dead wood and leaves do not decompose easily in the sea conditions and over time it develops into a dense carbon stock buried in marine sediments called blue carbon, which is stored for centuries and even thousands of years (CBD 2015). In this context, KAUST marine biologist Dr. Vincent Saderney mentioned the important factor of mitigating the damages of climate change that mangrove forests in the Red Sea dissolve soil carbonate six times more than in other parts of the world and moreover increase the total alkalinity of sea water and enhance its ability to store carbon dioxide from the atmosphere, thus reducing ocean acidity raise and global warming; furthermore, it helps to control the Earth's temperature (CBD 2015). At the beginning of this century, mangroves, seagrass, meadows and salt marshes were seen as insignificant components of the marine ecosystem, but now we understand how important they are in building blue carbon strategies to mitigate greenhouse gas emissions. Many countries are making significant efforts to protect and conserve these environments in order to fulfill their commitments under the Paris Climate Agreement (CBD 2015).

13.5.3 Soil Conservation

For soil protection and conservation forest and agroforestry activities considered to be the most efficient methods in addition to the other environmental function provided. It is worth to mention that carob roots, contrary to what is believed, do not contain active symbiotic bacterial nodules capable to fix atmospheric nitrogen; however, endomycorrhizae fungi of Arbuscular type grown on carob root has an important role in the nitrogenous and mineral nutrition of its trees, especially in poor soils, as in the case of the Mediterranean regions, where growth and productivity are limited by climate and other factors (Konate 2007). Fruiting pine used for decoration and fixing beach sand dunes, as well as it plays an important role in preserving the soil, especially in the sandy slopes. Euphrates poplar is able to regulate and transport salt ions under high levels of salinity in the soil and for long periods (Chen 2001). It was found that the concentration of salts under the crown of the tree is about 2–3 times higher than its surroundings, as the roots of the Euphrates poplar absorb salts from the soil and concentrate them on the surface, and the salt accumulated on the ground prevents the growth of any neighboring plants. As discussed above in UAE, the halophytes as biosaline agroforestry play very important role in absorbing salt from saline environment and ameliorating the soil to a great extent, at times worth growing any arable crop on these lands.

13.5.4 Watershed Protection

Mountain watersheds, comprising a substantial proportion of national territories of countries in South Asia, are biophysical and socioeconomic entities, regulating the hydrological cycle, sequestrating carbon dioxide, and providing natural resources for the benefit of people living in and outside the watersheds. Watershed hydrologic behavior can be affected by forests and trees, in particular the quantity and quality of stream flow, erosion, and sedimentation. In general, natural forests harvest the highest quality of water of any ecology. In natural conditions, the lowest erosion and sedimentation levels are commonly associated with forested watersheds.

Trees preserve and protect the soil from the risk of water and wind erosion. Undoubtedly, these play an important role in soil conservation, even if it is found on a slope, where agroforest forms the barrier between rain and soil, for the canopy formed by its leaves and branches above the soil surface, so the trees receive the first shock of rain water, then it flows quietly on the leaves and trunks, and reaches the soil surface, where root aggregates give a cohesive structure to the soil, leading to the reduction of soil erosion in the forest to a minimum, moreover, the litter formed from the remnants of fallen leaves and branches forms a barrier resistant to the impact of rain and at the same time has a high absorbent force and increases the ability of the soil to infiltrate, and the decomposition of the litter material enriches the soil with humic acids, which in turn leads to the formation of highly stable soil complexes that improve the porosity and permeability of the soil (Dusan 1982). Therefore, forests must be protected from human exploitation, unregulated investment, fires, and complete deforestation to turn them into agricultural lands and protect them from overgrazing. In addition, the uncovered areas must be afforested and targeted to the agroforestry systems. Furthermore, Kbebo (2005) confirmed, through a comparison between the three ecosystems: forests, burnt forests, and cultivated soil, in seven separate locations in Lattakia Governorate from 1992 to 1998 that the high erosion amounts reach to scary limits of 115 Mg ha^{-1} $year^{-1}$, especially in barren soils and steep slopes. These numbers are much higher than the permissible limits in Syria. A comparison was also made between the percentages of water flowing on the surface of the soil, which amounted to 45% of the total precipitation water, especially the bare and steeply sloped soil. Kangarani (2005) gave a detailed account of economic, social and institutional aspects of forest in an integrated watershed management of Euphrates and Tigris watershed. It has been rightly pointed out that one must learn from the nature by its own that it never follows the policy of any government, never listens to the politician, never recognizes the political boarder and never changes their way because of any religious and political belief. To protect the nature, we must think like nature and take action strongly like nature. The watersheds must be developed with integrated approach adapting agroforestry practices and sharing of resources. The conflict of sharing of water may be resolved as agreed upon between the nations mentioned in the inventory published by Economic and Social Commission for Water of United Nations (UN-ESCWA 2013).

13.6 Conclusions

The Southwest Asia region is facing double crisis of land degradation due to deforestation and climate change which is more vulnerable because of the arid climates and coastal regions due to rise in sea level. Thus, the preservation and protection of natural resources (soil - water - vegetation cover) through agroforestry has become an urgent necessity to preserve the natural wealth of these regions. Rehabilitation of forest lands, especially degraded by drought and fire, with appropriate types of agroforestry systems with multiple benefits and purposes supporting rural families and residents of areas adjacent to forests is of utmost importance. There is a need to develop an integrated plan for the management of natural resources in general and water resources in particular, so these resources to be developed, rationalized and qualified for the development and protection of natural resources. The good future for agroforestry and industrial forests is related to the great attention received from the governments, working in support of the forest sector, although it enhances agroforestry to be expanded and developed. In saline areas, adoption of biosaline agroforestry through proper selection and domestication of high value species of trees, shrubs, grasses and plants of medicinal wealth needs priority. We need to develop accredited nurseries of improved germplasm and train different stakeholders. The interregional cooperation is must and needs priority at international level.

References

Abahussain AA, Abdu AS, Al-Zubari WK, El-Deen NA, Abdul-Raheem M (2002) Desertification in the Arab region: analysis of current status and trends. J Arid Env 51:521–545

Abbaslou H, Abtahi A, Peinado FJM, Owliaie H, Khormali F (2013) Mineralogy and characteristics of soils developed on Persian Gulf and Oman Sea Basin, Southern Iran: implications for soil evolution in relation to sedimentary parent material. Soil Sci 178:568–584

Abdoul-azize S (2016) Potential benefits of jujube (*zizyphus lotus* l.) bioactive compounds for nutrition and health. J Nutr Metab 2016:2867470. https://doi.org/10.1155/2016/2867470

Abdullah G R, Mammad S (2004) The effect of potassium fertilization on the productivity and quality of the fruits of Sidr grafted on the local Sidr in the Al-Ahsa Oasis. Department of Horticulture, College of Agricultural and Food Sciences, King Faisal University, Saudi Arabia, p. 124. (In Arabic)

Abido M (2009) The project of preparing the first national communication on climate changes: assessment of vulnerabilities and measures of adaptation to climate changes in Syria. Ministry of Administration and Environment and UNDP. 55 p

Afonso Do Ó, Bugalho M, Silva L (2009) Forest fires and climate change. WWF Mediterranean Program, Lisbon

Agricultural Statistical Group (2016) Ministry of agriculture and agrarian reform in the Syrian Arab Republic. (In Arabic)

Ali M (2008) The project of preparing the first national communication on climate changes: assessing the sensitivity of the forest sector to climate changes. Ministry of Local Administration and Environment and UNDP. 41 p

Allbed A, Kumar L, Shabani F (2017) Climate change impacts on date palm cultivation in Saudi Arabia. J Agrl Sci 155(8) https://www.cambridge.org/core/journal-of-agricultural-science

Al-Obaidi A (2000) Rare fruits. Arab Publishing House, Cairo, pp 143–148. (In Arabic)

AOAD (2014) Arab agricultural statistics yearbook. Arab Organization for Agricultural Development, Khartoum. http://www.aoad.org/stat_ybook/34/Part1.pdf

Arab News (2021) Saudi Arabia's Al-Ahsa tree plantation drive in full swing. https://arab.news/c5ujs

Arab Organization for Agricultural Development (1994) Agroforestry systems. League of Arab States, Khartoum. 65 pages

Archaux F, Wolters V (2006) Impact of summer drought on forest biodiversity: what do we know? Ann For Sci 63:645–652

Arndt SK, Clifford SC, Popp M (2001) Ziziphus—a multipurpose fruit tree for arid regions. In: Becky SW, Vest M, Wucherer W (eds) Sustainable land use in the desert. Springer, Berlin, pp 388–399

Asgarpanah J, Haghighat E (2012) Phytochemistry and pharmacologic properties of *Ziziphus spina christi* (L.) Willd. Afr J Pharm Pharmacol 6(31):2332–2339

Ayben K, Harzemsah H, Hubert K, Siegfried N (2004) Volatile constituents and key odorants in leaves, buds, flowers, and fruits of *Laurus nobilis* L. J Agric Food Chem 52(6):1601–1606

Backlund P, Janetos A, Schimel DS, Hatfield J, Ryan MG, Archer SR, Lettenmaier D (2008) Executive summary. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC. 362 pp

Barreira JCM, Casal S, Ferreira ICFR, Oliveira MBPP, Pereira JA (2009) Nutritional, fatty acid and triacylglycerol profiles of *Castanea sativa* Mill. cultivars: a composition and chemometric approach. J Agric Food Chem 57:2836–2842. https://doi.org/10.1021/jf803754u

Battle I, Tous J (1997) Carob tree (*Ceratonia siliqua* L) promoting the conservation and use of underutilized and neglected crops. Institute of Plant Genetics and Crop Plant Research, International Plant Genetic Resources Institute, Rome

Borelli S, Cnigliaro M, Quaglia S, Salbitano F (2017) Urban and peri-urban agroforestry as multi-functional land use. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 705–724
CBD (2015) The 5th national report of West Asia countries. Secretariat of the Convention on Biodiversity, UN
CCSP (2008) The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States (U.S. Climate Change Science Program Synthesis and Assessment Product 4.3)
Chen S (2001) Salt nutrient uptake and transport and ABA of *Populus euphratica*, a hybrid in response to increasing soil NaCl, Abstract. Springer
Cherlet M, Hutchinson C, Reynolds J, Hill J, Sommer S, von Maltitz G (eds) (2018) World atlas of desertification. Publication Office of the European Union, Luxembourg
Clarke H (2007) Conserving biodiversity in the face of climate change. Agenda 14(2):157–170
Correia PJ, Martin-Loucao AM (2005) The use of macronutrients and water in marginal Mediterranean areas: the case of carob-tree. Field Crops Res 91:1–6
Dagar JC, Minhas PS (eds) (2016) Agroforestry for management of waterlogged saline soils and poor-quality waters. Advances in agroforestry, vol 13. Springer, Dordrecht, p 210
Dagar JC, Tewari VP (eds) (2017) Agroforestry: anecdotal to modern science. Springer, Singapore, p 879
Dagar JC, Singh AK, Arunachalam A (eds) (2014) Agroforestry systems in India: livelihood security & ecosystem services. Advances in agroforestry 10. Springer, New York, p 400
Dagar JC, Lal K, Kumar M, Ram J, Chaudhari SK, Yadav RK, Singh G, Ahamad S, Kaur A (2016) Impact of eucalyptus geometry on biomass production, water table drawdown, carbon sequestration and inter-crop yield on waterlogged saline soils of North-West India. Agric Ecosyst Environ 233:33–42
Dagar JC, Yadav RK, Sharma PC (eds) (2019) Research developments in saline agriculture. Springer, Singapore, p 926
Dagar JC, Gupta SR, Teketay D (2020a) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, p 554
Dagar JC, Gupta SR, Teketay D (2020b) Agroforestry for degraded landscapes: recent advances and challenges, vol 2. Springer, Singapore, p 475
Dusan Z (1982) Soil erosion. Forest Research Institute, Zvolen
El Batal H, Hahib A, Ouatmane A, Jaouad A, Naimi M (2012) Rheology and influence factor of Locust Bean Gum solution. Revue de génie industriel 8:55–62
El-Juhany L, Aref I (2009) The natural forest in Southwest of Saudi Arabian Kingdom, King Saud University, Academia.edu. 6 p. (Arabic)
EOAR (2010) State of the biodiversity in West Asia. Environmental Outlook for the Arab Region. The Environment Outlook for the Arab Region (EOAR 2010). United Nations Environment Programme (Arabic version). http://www.unep.org/dewa/westasia/eoar/
Españaa MSA, Galdónb BR, Romerob CD, Rodríguez ER (2011) Fatty acid profile in varieties of chestnut fruits from Tenerife (Spain). J Food 9(1):77–81. https://doi.org/10.1080/19476331003686858
Fady B, Finesch S, Vendramin G (2004) Italian stone pine—*Pinus pinea*: technical guidelines for genetic conservation and use (PDF), European Forest Genetic Resources Programme
FAO (2010) Forests around the world (In Arabic). FAO, Rome
FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW)—managing systems at risk. Food and Agriculture Organization of United Nations, Rome
FAO (2015) Status of the world's soil resources (SWSR)—main report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome
FAO (2017) Agroforestry for landscape restoration—exploring the potential of agroforestry to enhance the sustainability and resilience of degraded landscapes. FLRM—forest and landscape restoration mechanism. Food and Agriculture Organization of the United Nations, Rome

FAO (2019) Forest land scape restoration in the Caucasus and Central Asia. United Nations Economic Commission for Europe (UNECE) and FAO, New York

FAOSTAT (2019) USDA food data. www.fao.org/faostat/en/#data/QC

Gerardi C, Tommasi N, Albano C, Blando F, Rescio L, Pinthus E, Mita G (2015) *Prunus mahaleb* L. fruit extracts: a novel source for natural food pigments. Eur Food Res Technol 241(5): 683–695. https://doi.org/10.1007/s00217-015-2495-x

Greenprophet (2020). https://www.greenprophet.com/2020/08/the-al-baydha-project-how-regenerative-agriculture-revived-green-life-in-a-saudi-arabia-desert/

Gupta SR, Dagar JC, Jangra R, Gaur A (2019) Tree-based systems for enhancing environmental services of saline environments. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer, Singapore, pp 461–502

Hayek M (1999) Encyclopedia of medicinal plants. First Dictionary, Library of Lebanon, pp 355–460. (In Arabic)

Hsu H (1980) Commonly used Chinese herb formulas with illustrations. Orient Healing Arts Institute, Long Beach (28), pp 42–46

IPCC (2001) Climate change 2000. Contribution of Working Group II to the third Assessment Report of Intergovernmental panel on Climate Change. p 45

IPCC (2021) Summary for policymakers. In: Masson-Delmotte et al (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press

Ishag YMA (2021) Physiochemical characterization of Ziziphus spina-cristi fruit pulp (Nabag). A thesis in partial fulfillment of the requirement of Master in Chemistry. Sudan Univ of Sci and Technology

Ismail S, Rao NK, Dagar JC (2019) Identification, evaluation and domestication of alternative crops for saline environment. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer Singapore p 505–536

Kangarani HM (2005) Euphrates and Tigris watershed economic, social and institutional aspects of forest in an integrated watershed management. Working paper. FAO, Rome

Kbebo I (2005) Soil conservation and the importance of vegetation cover in reducing erosion and increasing water reserves in the coastal area. Soil and land reclamation symposium. Faculty of Agriculture Aleppo University in cooperation with the Arab Organization for Agricultural Development, ACSAD, General Commission for Scientific Agricultural Research and ICARDA, 27-29/3

Kebely I (1998) Carob tree *Ceratonia siliqua* L. its botanical characteristics—its environment—its benefits—its propagation. J Agric Water Dry Areas Arab World. Arab Center for Studies of Arid Zones and Dry Lands. Oxidation (18)

Kipp E (2008) Heat stress effects on growth and development in three ecotypes of varying latitude of Arabidopsis. App Ecol Environ Res 6(4). https://doi.org/10.15666/aeer/0604_001014

Konate I (2007). Diversité Phénotypique et Moléculaire du Caroubier (*Ceratonia siliqua* L.). et des Bactéries endophytes qui lui sont associées. Université Mohammed V-Agdal Faculté Des Sciences Rabat, thèse de doctorate

Leontiades LI (1989) Traditional agroforestry practices under the edaphoclimatic parameters of Cyprus. In: Reifsnyder WS, Darnhofer TO (eds) Meteorology and agroforestry. Proc International workshop on the application of meteorology to agroforestry systems planning and management (9–13 Feb, 1987). ICRAF, Nairobi, pp 233–240

Lo SP (2008) How dangerous is dangerous climate change? From the international conference workshop on biodiversity and climate change in Southeast Asia: adaptation and mitigation, 19–20 February 2008, Sofitel Philippine Plaza, CCP Complex Manila, p 10

Losey AP, Jurina LL (2003). Agro-metrology. M Koloc, p 301

Makhoul G, Mahfoud M (2000) Al-Anab and its requirements. Al-Muhandis Al-Arabi J Tishreen, Lattakia, Syria, p 3. (In Arabic)

Malmsheimer WR, Bowyer LJ, Fried SJ, Gee E, Izlar LR, Miner AR, Mun AI, Oneil E, Stewart CW (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. A Society of American Foresters Task Force Report. J For 109(7S):7–51

Mariana S, Alirio R, Jose AT (2005) Production of dextran and fructose from carob pod extract and cheese whey by *Leuconostoc mesenteroides*. NRRL B512 (f). Biochem Eng J 25:1–6

Mckengie D, Gedalof ZM, Peterson DL, Mote PW (2004) Climate change, wildfires, and conservation. Conserv Biol 18(4):890–902

Mead DJ (2009) Agroforestry. In: Forest and forest plants, vol I

Ministry of Environment Protection of Georgia (2015). Georgia's intended nationally determined contribution submission to the UNFCCC. http://www4.unfccc.int/Submissions/INDC/Published%20Documents/Georgia/1/INDC_of_Georgia.pdf

Minkov S, Gradinarska E, Lozarska N (1968) NO (8):141–146

Mirzabaev A, Wu J, Evans J, García-Oliva F, Hussein IAG, Iqbal MH, Kimutai J, Knowles T, Meza F, Nedjraoui D, Tena F, Türkeş M, Vázquez RJ, Weltz M (2019) Desertification. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Montagnini F (2006) Homegardens of Mesoamerica: biodiversity, food security, and nutrient management. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time-tested example of sustainable agroforestry. Advances in agroforestry 3. Springer, Dordrecht, pp 61–84

Montagnini F, Jordan CF (2005) Tropical forest ecology. The basis for conservation and management. Springer, Berlin, p 295

Montagnini F, Nair PK (2004) Carbon sequestration: an under-exploited environmental benefit of agroforestry systems. Agrofor Syst 61:281–295

Murgueitio E, Calle Z, Uribe F, Calle A, Solorio B (2011) Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manag 261(10):1654–1663

Mutke PM, Calama R (2013) Mediterranean stone pine for agroforestry. Mediterranean Seminars Number 105

Nahal I (2002) Forest ecology. Directorate of University Books and Publications, Publications of the Faculty of Agriculture, University of Aleppo, pp 220–223

Nahal I (2003) Dendrology. Aleppo University Publications, Faculty of Agriculture, 630 pages. (In Arabic)

Nahal I (2012) Encyclopedia of forest wealth in Syria (past-present-future prospects). Publications of the Food and Agriculture Organization of the United Nations, Damascus-Syria, 480 pages. (In Arabic)

Nahal I, Rahma A, Shalaby N (1989) Foresters and forest nurseries. Publications of the Faculty of Agriculture, Aleppo University. 600 pages. (In Arabic)

Nair PKR, Kumar MK, Nair VD (2021) An introduction to agroforestry: four decades of scientific development, 2nd edn. Springer, Cham, p 666

Nally MR, Cunningham S, Shelly K, Sgrò C, Thompson R, Lake S, Sunnucks P, Cavagnaro T, O'Dowd D, Baker P, Beardall J (2008) Biodiversity and climate change. The Australian Center for Biodiversity, Monash University, Victoria, p 17

Naser H (2014) Chapter 12: marine ecosystem diversity in the Arabian Gulf: threats and conservation. In: Grillo O (ed) Biodiversity—the dynamic balance of the planet. http://www.intechopen.com/books/biodiversity-the-dynamic-balance-of-the-planet/marine-ecosystem-diversity-in-the-arabian-gulf-threats-and-conservation

Papaefstathiou E, Agapiou A, Giannopoulos S, Kokkinofta R (2018) Nutritional characterization of carobs and traditional carob products. Food Sci Nutr 6(8):2151–2161

Peñuelas J, Filella I, Zhang X, Llorens L, Ogaya R, Lloret F, Comas P, Estiarte M, Terradas J (2004) Complex spatiotemporal phenological shifts as a response to rainfall changes. New Phytol 161: 837–846

PERSGA (2015) Status of mangroves in the Red Sea and Gulf of Aden. PERSGA-The Technical Series of the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden

Prăvălie R (2016) Drylands extent and environmental issues. A global approach. Earth-Sci Rev 161: 259–278

Qureshi AS, Ismail S (2017) Prospects of agroforestry for the marginal environments: evidences from the United Arab Emirates. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 455–475

Randhir TO, Erol A (2013) Emerging threats to forests: resilience and strategies at system scale. Am J Plant Sci 4(3):739–748

Raodh M, Alia Z, Faleeha H (2014) The antioxidant and antimicrobial activity of Syrian sumac (*Rhus coriaria*) fruit extract. J Nat Sci Res 4:36–40

Rebetez M, Mayer H, Dupont O, Schindler D, Gartner K, Kropp PJ, Menze A (2006) Heat and drought in Europe: a climate synthesis. Ann For Sci 63:569–577

Roshetko JM, Lasco RD, Delos Angeles MD (2007) Smallholder agroforestry systems for carbon storage. Mitig Adapt Strateg Glob Chang 12:219–242

Sakhr K, El Khatib S (2020) Physiochemical properties and medicinal, nutritional and industrial applications of Labanese Sumac (Syrian Sumac-*Rus coriaria*): a review. Heliyon 6:e03207. https://doi.org/10.1016/j.heliyon.2020.e03207

Santos M, Rodringus A, Teixeira JA (2005) Production of dextran and fructose from carob pod extract and cheese whey by *Leuconostoc mesenteroides* NRRL. B512 (f). Biochem Eng J 25(1): 1–6

Sileshi GW, Mafongoya PL, Ajayi OC (2020) Agroforestry systems for improving nutrient cycling and soil fertility on degraded lands. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, pp 225–253

Tengberg M (2002) The importation of wood to the Arabian Gulf in antiquity. The evidence from charcoal analysis. Proc Seminar Arabian Stud 32:75–81

Thevs N, Strenge E, Aliev K, Eraaliev M, Lang P, Baibagysov A, Xu J (2017) Tree shelterbelts as an element to improve water resource management in Central Asia. Water 9. https://doi.org/10.3390/w9110842

Tolba MK, Saab NW (2009) In: Tolba MK, Saab NW (eds) Arab environment: climate change: impact of climate change on Arab countries: 2009 report of the Arab Forum for Environment and Development. Arab Forum for Environment and Development. http://www.afedonline.org/afedreport09/

Tolunay A, Alkani H, Korkmazi M, Filizbilgin S (2007) Classification of traditional agroforestry practices in Turkey. Int J Nat Eng Sci 1(3):41–48

Trenberth KE (1998) Atmospheric moisture residence times and cycling: implications for rainfall rates with climate change. Climate Change 39:667–694

UCLG and UCLG-MEWA (2019) the GOLD V regional report on Middle East and West Asia

UN (2019) World population prospects. United Nations

UNDESA (2017) World population prospects 2017 revision

UNEP (2010) Ecosystem management: integrated solutions for biodiversity, climate change and poverty. (POLICY BRIEF 1–2010), p 15

UNEP (2016) GEO-6 regional assessment for West Asia. United Nations Environment Programme, Nairobi

UN-ESCWA (2013) Inventory of shared water resources in Western Asia. United Nations Economic and Social Commission for Western Asia, New York

Urdiain M, Donenech-Sanchez A, Albert S, Benedi VJ, Rossello JA (2004) Identification of two additives Locust Bean Gum (E – 410) and Guar Gum (E – 412), in food products by DNA-based methods. Food Addit Contam 21(7):619–625

USGCRP (2009) Global climate change impacts in the United States. In: Karl TR, Melillo JM, Peterson TC (eds) United States Global Change Research Program. Cambridge University Press, New York

Verchot LV, Van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strateg Glob Chang 12:901–918

Wallery EG (2012) North Carolina's emergıng forest threats: management options for healthy forests

Worbes M, Botman E, Khamzina A, Tupitsa A, Martius C, Lamers JPA (2006) Scope and constraints for tree planting in the irrigated landscapes of the Aral Sea Basin: case studies in Khorezm Region, Uzbekistan. ZEF discussion papers on development policy, p 112

World Atlas (2022). worldatlas.com/articles/which-communities-are-parts-of-western-asia.html

Zohary D, Hopf M, Weiss E (2012) Domestication of plants in the old world: the origin and spread of domesticated plants in Southwest Asia, Europe, and the Mediterranean basin. Oxford University Press. https://global.oup.com/academic/product/domestication-of-plants-in-the-old-world-9780199549061?cc=ke&lang=en&

Zomer RJ, Trabucco A, Coe R, Place F, van Noorwijk M, Xu J (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. ICRAF Working Paper No. 179. ICRAF, Nairobi

Chapter 14
Achieving Biodiversity Conservation, Livelihood Security and Sustainable Development Goals Through Agroforestry in Coastal and Island Regions of India and Southeast Asia

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Abstract Coastal and island habitats are among the most fragile and climate-vulnerable ecosystems in the world which host around 2.4 billion people. This fragile ecosystem has been experiencing social, economic and environmental difficulties due to climate change-related vagaries such as sea-level rise, extreme weather events, ocean acidification and warming of sea surface temperatures. Coastal habitats are also threatened by population growth, expansion of residential, industrial and tourism developments and attendant pollution and habitat loss. Agroforestry has emerged as a potential remedial measure to address some of these issues, and to achieve at least nine out of seventeen sustainable developmental goals set by the United Nations. Practising agroforestry in coastal regions can stabilize food supplies and incomes through diversification, biodiversity conservation and providing physical protection against extreme weather events. Planting trees also helps to mitigate and adapt to climate change. This chapter highlights the importance of various agroforestry systems for biodiversity conservation, livelihood security, carbon sequestration and meeting some of the important sustainable development goals.

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14.1 Introduction

The coastline, which lies at the confluence of land and water, is undoubtedly one of the most complex and dynamic ecosystems on the planet earth. The coastal region, which is made up of a variety of interacting ecological, socio-cultural, economic and political systems, is always dynamic in nature. The global coastline is estimated to be about 620,000 km and over one-third of the world's population (nearly 2.4 billion people) living in coastal areas (within 100 km of an oceanic coast) that account for roughly 4% of the Earth's total surface area (www.worldatlas.com). The coastal ecosystems are critical to humanity's existence and provide a variety of ecosystem services that benefit both the environment and peoples' livelihoods like buffering against storm surge, stabilizing coastal and near-shore areas against erosion, serving as nursery habitats for commercially important fish species and supporting livelihoods and economic activities, such as tourism and fishing (UNEP 2006; UNEP-WCMC 2006). Coastal habitats are being threatened by anthropogenic factors such as population boom, industrial and tourism development, and attendant pollution, habitat and biodiversity loss due to deforestation, changes in access rights, markets, and technology, and climate change (Campbell et al. 2006). Despite of tremendous biotic interferences, the coastal and island ecosystems provide excellent niche for rich biodiversity. Various plantation crops like coconut (*Cocos nucifera*), arecanut (*Areca catechu*), cocoa (*Theobroma cacao*), cashew nut tree (*Anacardium occidentale*) and oil palm (*Elaeis guineensis*); spices like black pepper (*Piper nigrum*), cardamom (*Elettaria cardamomum*), clove (*Syzygium aromaticum*), ginger (*Zingiber officinale*), turmeric (*Curcuma domestica*); and seed spices like cumin (*Cuminum cyminum*), coriander (*Coriandrum sativum*), fennel (*Foeniculum vulgare*), chillies (*Capsicum acuminatum, C. annuum*); fruits such as banana (*Musa paradisiaca*), pine apple (*Ananas comosus*), sapota (*Achras zapota*), custard apple (*Annona squamosa*), and mango (*Mangifera indica*), and a variety of vegetables provide sustainability and nutritional security to the coastal population, mainly the poor folk (Dagar et al. 2014, 2020). The rich biodiversity harboured by agroforestry systems is intimately linked with people's livelihoods. Home gardens are like backyard supermarket which provides spices, oils, medicines, nuts, rubber, fruit, resins and agricultural implements.

Coastal and island habitats are among the most fragile and climate-vulnerable ecosystems. The agriculture and its allied sectors are mainly affected due to natural disasters like cyclones, landslides, flooding, drought, sea-level rise, coastal erosion, coastal pollution, low productivity of agricultural and horticultural crops, livestock and over-exploitation of the fishery resources. Agroforestry is considered as climate resilient and climate smart agricultural practice where in woody perennials are integrated with agricultural crops/animals including fishery in spatial arrangements or temporal sequences to achieve sustainable food production. Adoption of suitable agroforestry practices involving plantation crops, fruit and forest trees, spices, arable crops, forages, animals, poultry, apiculture, fish and shrimp culture plays a crucial role in improving the agricultural production and environmental protection and conservation and amelioration of the natural resource bases. Liu et al. (2019) reported that livelihoods and food security had been the focus of agroforestry research in Southeast Asia to address the challenges of rapid population growth. A recent bibliometric analysis of SE Asia agroforestry revealed that between 1980 and 2000, agroforestry studies focused on describing agroforestry models, the attributes of agroforestry species, and the benefits of agroforestry for the environment and local livelihoods (FAO 2021). In the decade of 2001–2010, more studies emerged on linking agroforestry with agro-biodiversity, climate-change mitigation and adaptation, and ecosystem services. In last decade (2011–2020), agroforestry studies were mostly focused on themes of regional and global concern such as food security and mitigation and adaptation. Agroforestry has the potential to improve rural livelihoods by providing small and marginal farmers with a variety of options and opportunities to increase farm productivity and income while conserving biodiversity and the environment. It is estimated that about 1.2 billion people (20%) of the world population depends directly on agroforestry products and services in developing countries which can provide goods and services that can offset 5–20% of deforestation (Leakey and Sanchez 1997; Dixon 1995). Agroforestry has the capability to increase the productivity and at the same time maintain the nutrient balance as well as protect the coastal environment. There is an intimate link between the biodiversity and livelihood security and the more diverse the system more it can cope up with changing climate and also assuring nutritional and livelihood security. Some of these aspects have been dealt in this chapter.

14.2 General Characteristics of Coastal Regions of India and SE Asia

In the coastal regions, population density is higher and about 50–70% of the global population lives within 100 km of the coastline covering only about 4% of earth's land (Naik et al. 2013). There are estimates that, coastal areas (within 200 km from the sea) share less than 15% of the earth surface area and about three-fourths of the world population is expected to reside in the coastal areas by 2025.

Southeast Asia is one of the most complex areas in the world and is composed of continental plates and oceanic plates. The region possesses about 80% mountains and hills, 5% plateaus and only 15% plains and swamps (Hinkel et al. 2013). The population of Southeast Asia is mainly distributed in the delta areas with low elevations. The region is widely accepted to be one of the most sensitive and vulnerable regions affected by climate change due to its large population and ecological pressure and surrounded by the ocean (Hallegate et al. 2013). Further, the urbanization has continued in recent decades, especially in large cities along the coast. Agriculture, forestry, animal husbandry, fishery, mining, processing industries, and international trade and tourism have been the major attractions involving plantation crops and mineral resources such as oil, natural gas, tin and copper (Zhang and Hou 2020).

Indonesia comprises approximately 13,450 islands covering some 200 million ha of land, of which 31.5% is farmland and 51% is forested (FAO 2015) and has the fourth largest population in the world (260 million) spread primarily across its five largest regions (Kalimantan (Indonesian Borneo), Sumatra, Papua (Indonesian New Guinea), Sulawesi, and Java), with a per capita GDP that has risen from US$ 807 in 2000 to US$ 3877 in 2018, making it the largest economy in Southeast Asia (World Bank 2019). Despite Indonesia's economic growth, it faces on-going challenges in relation to poverty and malnutrition, with 36.1% of Indonesians living below the poverty line and 30.5% of those under-5 year suffering from wasting or stunting (UNICEF 2020). In a well-conducted study, Duffy et al. (2021) emphasized that agroforestry has potential for strengthening the climate change resilience of smallholder farmers in Southeast Asia in general and in Indonesia in particular and the food security challenges faced by smallholders will likely worsen due to climate change impacts. Agroforestry provides an option for strengthening climate change resilience, while contributing to food access, income, health, and environmental stability.

The total length of coastline of India is 7516.6 km, of which 5422.6 km is with mainland and 2094 km is for Island territories (Mukhopadhyay and Karisiddaiah 2014; Naik et al. 2013; Rodriguez and Sridhar 2010; SAC 2012). The coastal region of India has nine states namely Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha and West Bengal and three union territories namely Daman and Diu, Dadra and Nagar Haveli and Puducherry. The island territories included in the coastal ecosystems are Andaman and Nicobar Islands (Bay of Bengal) and Lakshadweep (Arabian Sea). There are total of 67 coastal districts in mainland states, 7 districts in mainland union territories, 3 districts in Andaman and Nicobar Islands and 1 district in Lakshadweep. The total population of the coastal districts of India is 195 million, which is 16.16% of the total population of India (Census of India 2011).

14.3 Major Agroforestry Systems and Practices

The Southeast Asian region is often described as the cradle of agroforestry in recognition of its long history of the practice of an array of systems under diverse agroecological conditions (Kumar et al. 2012). Multifunctional home gardens, which promote food security and diversity; woody perennial-based multi-tiered systems, which promote employment opportunities; integrated tree-grass/crop production systems, which promote resource conservation; and tree-dominated habitats, which sustain agrobiodiversity and mitigate climate change, are all prominent examples of agroforestry in Southeast Asia (Table 14.1).

Table 14.1 Major agroforestry practices in India and Southeast Asia

Country	Major agroforestry practices
India	Home gardens, hedgerow intercropping, plantation-based multi-storied cropping systems, silvopastoral systems, shelterbelts, woodlots, live fences and hedges, multi-enterprise farming systems, farming in forests
Brunei Darussalam	Forest farming, mixed-species plantation
Cambodia	Taungya, alley cropping, forest farming, home garden
Indonesia	Tumpangsari, multi strata cocoa, mixed fruit tree agroforestry, home garden, forest garden, jungle rubber, agrosilvofishery
Lao PDR	Shifting cultivation, intercropping, mixed-species plantation, home garden
Malaysia	Taungya, home gardens, hedge row intercropping, fruit tree and mixed-species plantation, tree-based pasture, apiculture with trees
Myanmar	Taungya, mixed-species plantation, alley cropping, tree-based aquaculture
Philippines	Alley cropping, taungya, multi-storey system, tree–crop grazing system, SALT, natural vegetative strips, woodlots
Thailand	Shifting cultivation, home garden, taungya, mixed-species plantation, forest farming , improved fallows, multi-enterprise farming systems
Viet Nam	Shifting cultivation, taungya, tree-based aquaculture and pasture, home garden

Source: FAO (2021)

According to the ISFR (2013) report, around 18% of the total agroforestry area in India is found in coastal regions (Fig. 14.1), 12% of that lies in western coast and 6% in east coast. The west coast of India is rich in biodiversity as it hosts Western Ghats, one of the mega hot-spot on earth. Many workers have examined and recognized a variety of agroforestry systems and practises ideal for coastal and island areas (Nair and Sreedharan 1986; Dagar 1991, 1994, 1995, 1996, 2000; Kumar 2005, 2011; Kumar et al. 1998, 2001a, b, 2005; Pandey et al. 2007; Kumar and Kunhamu 2011; Dagar et al. 2014, 2020; Dagar and Minhas 2016). Agroforestry trees supply raw resources to a variety of businesses and have the immense potential to increase and sustain the food production per unit area. The diversification through tree-based systems provides opportunity to get multiple outputs such as food, fruits, fibre, fertilizers, fuelwood and fodder. Coconut, arecanut, rubber, tea, coffee, cardamom, and oil palm are important plantation crops in coastal areas, where the combination of crown architecture and the wide spacing provide possibilities of introduction of inter crops in association with them. Home gardens provide diversity of products significant in improving food security directly or indirectly. The major agroforestry systems in the coastal regions of SE Asia and their components are explained in Table 14.2.

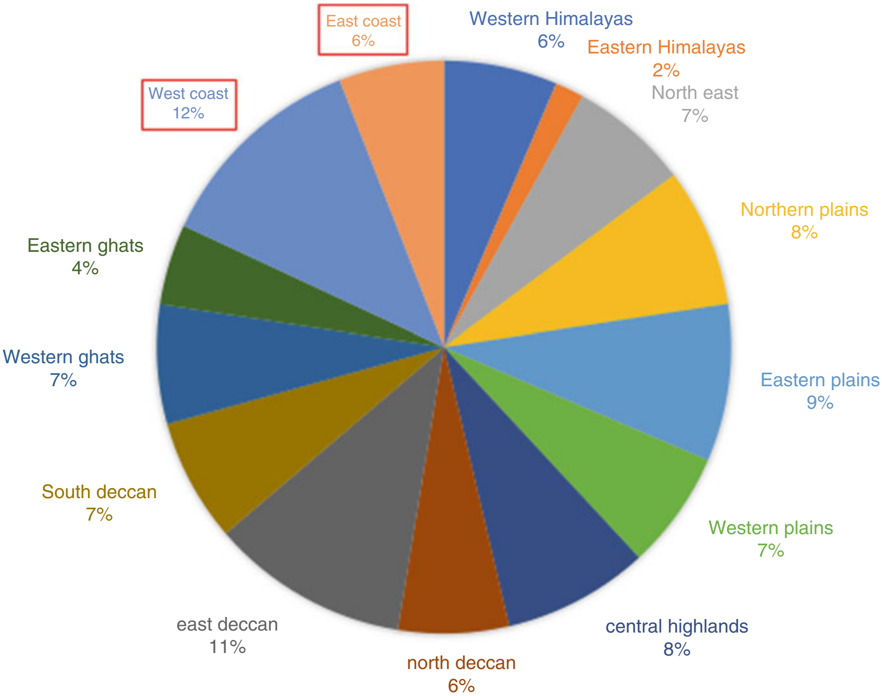


Fig. 14.1 Percent area under coastal and island agroforestry in India. (Source: ISFR 2013)

14.3.1 Home Gardens

Home gardens are an integral part of farming system, an adjunct to the house, where selected trees, shrubs and herbs are grown for edible products and cash income (Kumar and Nair 2004). They are common in the entire Southeast Asian region (Fig. 14.2a–c). It's an operational farm where a variety of products, such as food and cash crops, vegetables and tree crops, are cultivated along with livestock, poultry, and/or fish production, mostly to meet the farmer's basic needs. The components of a homestead are so intimately mixed in horizontal and vertical strata as well as in time that a number of complex interactions exist among soil, plants, water, other components and environmental factors in the farmer's plot where he lives and manages the unit (Nair and Sreedharan 1986; Nair and Dagar 1991; Krishnakumar 2004). Home garden in addition to plantation and fruit trees includes poultry, livestock, and fish-pond. Home gardens are a popular land-use pattern in Andaman and Nicobar Islands also, accounting for 63% of arable land (Basic Statistics 2001). Net income in the home gardens of Andaman was 6.9 times higher compared to that in the home gardens of Nicobar (Pandey et al. 2007). It was estimated that around 6.6–50.8 m^3 ha^{-1} of standing commercial timber and about 23–86 m^3 ha^{-1} fuel wood was present in home gardens of Kerala (Kumar et al. 1994). Pandey et al.

Table 14.2 Major agroforestry systems in the coastal and island regions of India and Southeast Asia

Agroforestry practices	Region/country	Agroforestry components	Reference
Home gardens	West Godavari, Andhra Pradesh, India	Coconut, MPTs with crops, grasses	Alavalapati et al. (1995)
	Goa	MPTs + plantations	Dagar et al. (2014)
	Andaman and Nicobar Islands	• Plantations, MPTs, spices, fruits, vegetables, poultry, grasses + Japanese quail (*Coturnix japonica*) Aqua silviculture • Home gardens (arecanut–coconut–rice; arecanut–coconut; coconut–Gliricidia–vanilla; coconut–Gliricidia–black pepper; vegetables; coconut–tuber type) • Coconut + local pig + poultry Black pepper under Gliricidia in coconut	Venkatesh et al. (2010) Dagar et al. (2020) Pandey et al. (2005, 2007) Pandey and Singh (2010)
	Lakshadweep	Coconut + grasses + vegetables + fruit + poultry	John et al. (2018)
	Purba Medinipur, West Bengal	MPTs + vegetables + fish	Dhara et al. (2016)
	Gujarat coastal lowlands	MPTs + grasses + vegetables	Singh et al. (2017)
	Palghat, Kerala	Coconut + fruit + MPTs	Peyre et al. (2006)
	Coastal Southeast Thailand	Mixed garden	Dumrongrojwatthana et al. (2020)
	Kampung Lingkungan, Sabah, Malaysia	Mixed gardens	Salma et al. (2006)
	Citarum Watershed of Indonesia	Plantations + fruit + poultry	Abdoellah et al. (2006)
	Java, Indonesia	Plantations + MPTs + fish	Jensen (1993)
	Saparua island, Central Maluku, Indonesia	Forest gardens	Kaya et al. (2002)
	Central Sulawesi, Indonesia	Mixed plantations	Kehlenbeck and Maass (2004)
	Upper Citarum Watershed, West Java, Indonesia	*Kebon tatangkalan* (mixed tree garden)	Parikesit et al. (2005)
Plantation-based multi-storied cropping systems	Central Kerala	Pineapple, banana and vegetables intercropped with rubber in early establishment stage; coffee and cocoa in mature stage	Siju et al. (2012)

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
	Central Kerala	Pineapple-rubber	Ulahannaan et al. (2014)
	Thrissur, Kerala	Cocoa (*Theobroma cacao*) clones under arecanut and coconut	Apshara (2013)
	Wayanad, Kerala	Black pepper on *Erythrina*/*Acacia mangium*/coconut	Kumar (2007)
	Palghat, Kerala	Turmeric, cardamom, black pepper in areca nut	Sujatha et al. (2011)
	Wayanad, Kerala	Areca+cocoa+banana; Areca-banana-cocoa -black pepper; Areca-cardamom	Bhat et al. (2014)
		Shaded coffee/tea/nutmeg/clove	Kumar (2007)
		Shaded tea	
		Banana, cacao, black pepper, pineapple, betel vine, elephant foot yam, tapioca, paddy, sorghum, cowpea, vegetables, turmeric, ginger and guinea grass under oil palm or arecanut	
	Thrissur, Kerala	Galangal/turmeric/ginger under coconut/rubber/cashew	Kunhamu et al. (2015)
	Kasaragod, Kerala	Mixed cropping of noni under coconut	Maheswarappa et al. (2017)
		Heliconia, Anthurium, Jasminum under coconut	Maheswarappa et al. (2010)
		MPTs like *Acacia mangium, A. auriculiformis, Casuarina, Ailanthus* sp., teak, tamarind and *Erythrina indica* under coconut	
		Black pepper, vanilla, nutmeg, cinnamon, clove under coconut	
		Pepper/clove/nutmeg/cocoa under coconut	
		Banana/pineapple under coconut	
		Cassava, elephant foot yam, colocasia, Chinese potato, sweet potato, greater yam and lesser yam under coconut	
		Soybean/ groundnut under coconut	
		Cocoa-coconut	

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
		Coconut+ cocoa+ pineapple+ black pepper	
		snake gourd, bottle gourd, brinjal, Coccinia and bitter gourd under coconut	
		Banana+ black pepper+ pine apple + nutmeg + coconut	Nair et al. (2018)
	Hilly coastal Kerala	Coffee, vanilla, *Garcinia* and nutmeg under rubber	Jessy et al. (2017)
		Amaranthus/salad cucumber under rubber	Jessy et al. (2017)
	Kasaragod, Kerala	Coconut + Jasminum	Arunachalam and Reddy (2007)
	Ratnagiri, Maharashtra	Lesser yam, greater yam, aerial yam, elephant foot yam and tapioca under cashew plantation	Gajbhiye et al. (2018)
	Ratnagiri, Maharashtra	*Morinda citrifolia* as mixed crop in coconut	Khandekar et al. (2015)
	Puri, Odisha	Coconut + banana + tuberose (in young coconut plantations)	AICRP (Palms) (2018)
	Villupuram	Coconut + banana + turmeric + elephant foot yam + pineapple + tapioca + okra	AICRP (Palms) (2018)
	South 24 Parganas, West Bengal	Coconut + black pepper + pine-apple Coconut + black pepper + lime + pineapple + banana + turmeric + elephant foot yam	AICRP (Palms) (2018)
	Prakasam, Andhra Pradesh	Coconut + cocoa + banana + pineapple + tomato	AICRP (Palms) (2018)
	East Godavari	Medicinal and aromatic crop (citronella, lemongrass, palmarosa, patchouli, mango ginger) intercropping under coconut plantations	Padma et al. (2018)
	Goa	*Heliconia* under coconut	Thangam et al. (2014)
		Coconut-based farming	John et al. (2018)
		Noni-coconut mixed cropping	
	South Andaman	Black pepper under Gliricidia in coconut	Pandey and Singh (2010)
	Andaman and Nicobar	Noni-coconut mixed cropping	Jaisankar et al. (2017)
	Andaman and Nicobar	Plantation-based multi-storied cropping	Dagar (2000)
	Dakshina Kan-nada, Karnataka		Apshara (2013)

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
		Cocoa (*Theobroma cacao* L.) clones under arecanut and coconut	
	Kanara, Karnataka	Areca+ cocoa + banana	Bhat et al. (2014)
		Areca-banana-cocoa-black pepper	
		Areca-cardamom	
		Intercropping of Medicinal and Aromatic Plants	
	Dakshina Kannada, Karnataka	Arecanut + *Piper longum*; Arecanut + *Cymbopogon flexuosus*; Arecanut + *Vetiveria zizanoides*; Arecanut + *Asparagus racemosus*; Arecanut + *Bacopa monnieri*; Arecanut + *Nilgirianthus ciliate*; Arecanut + *Catharanthus roseus*; Arecanut + *Aloe vera*; Arecanut + *Cymbopogon martini*; Arecanut + *Ocimum basilicum;* Arecanut + *Pogostemon cablin*; Arecanut + *Artemisia pallens*	Sujatha et al. (2011)
	Navsari, Gujarat	Noni-coconut	Bhalerao et al. (2016)
	Sumatra	Rubber based	Beukema et al. (2007)
	Coastal Southeast Thailand	Lowland rice and palmyra palm	Dumrongrojwatthana et al. (2020)
	Central Sulawesi, Indonesia	Cocoa under Gliricidia or mixed trees	Köhler et al. (2014)
	Coastal Southeast Thailand	Lowland rice–palmyra palm–fisheries	Dumrongrojwatthana et al. (2020)
	Central Sulawesi, Indonesia	Shaded cocoa	Clough et al. (2009)
	Central Kalimantan, Indonesia	Rattan-based system	Afentina et al. (2020)
Silvopastoral systems	Thrissur, Kerala	Fodder trees and grasses under coconut or home gardens	Raj et al. (2016a, b)
		Fodder grasses and/or fodder bank trees in home gardens/ coconut garden	
	Khordha, Odisha	Silvopastoral system (Guinea, Thin Napier and *Setaria* as fodder crops with *Acacia mangium*, *A. auriculiformis* and *Samanea saman*)	Jwel et al. (2019)
	Goa, India	Fodder maize under cashew	Naik et al. (2011)

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
	Andaman and Nicobar	Grasses/vegetables under coconut	Dagar (2000)
		Livestock and fodder under home gardens	
		MPTs on farm	
	Navsari, Gujarat	Sapota-grass	Sureshbhai et al. (2017)
	Eastern Coastal Plain, India	*Gliricidia sepium and Leucaena leucocephala, Stylosanthes scabra*	Handa et al. (2019)
		Guava with Cenchrus ciliaris-based horti-pasture system for degraded lands	
	Kerala, India	*Morus indica* *Calliandra calothyrsus*	Handa et al. (2019)
	Coconut-based hortipastoral System	*Calliandra calothyrsus* *Cocos nucifera*	
Shelterbelts	North and Middle Andaman, South Andaman, Nicobar	Shelterbelts for shore protection Associate mangroves	Dagar (2000)
Farming in forests	Andaman and Nicobar, India	Farming in forest mainly spices + domestic pig + fruit	Dagar (2000)
Hedge row cropping	Thrissur, Kerala, India	Ginger—*Ailanthus triphysa*	Kumar et al. (2001b)
		Medicinal or aromatic plants under shade	Nair et al. (1991)
		Turmeric under *Dendrocalamus strictus* (8 m × 8 m)	Kittur et al. (2016)
	Ratnagiri, Kerala	Finger millet with *Dendrocalamus stocksii*	Rawat et al. (2017)
		Banana with eucalyptus	Agarwal et al. (2017)
		Subabul intercropping with beans	Agarwal et al. (2017)
	Sindhudurg, Kerala	Block planting of *D. stocksii* and *Bambusa balcoa*	Subbana and Viswanath (2018)
	Ratnagiri, Kerala	Mango + groundnut	Dalvi et al. (2019)
		Pseudoxytenanthera stocksii + finger millet *Pseudoxytenanthera stocksii* + cowpea	NRCAF (2014)
	Khordha, Odisha	*Dendrocalamus strictus* + black gram *Dendrocalamus strictus* + green gram *Dendrocalamus strictus* +	NRCAF (2014)

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
		sesame *Dendrocalamus strictus* + cowpea	
	Khordha, Odisha	*Casuarina equisetifolia* + watermelon	Roy Chowdhury et al. (2011)
	Bhadrak, Odisha	*Acacia auriculiformis* + paddy *A. auriculiformis* + pumpkin *A. auriculiformis* + brinjal *A. auriculiformis* + tomato	Shial and Mohapatra (2017)
		Silvihorticulture (*Casuarina* + teak + papaya; *Casuarina* + tamarind + drumstick; *Casuarina* + teak + *Eucalyptus* + guava)	Ravi et al. (2013)
	Cuddalore, Tamil Nadu	Agrisilvicultural system	Immanuel and Ganapathy (2010)
	Navsari, Gujarat	Ginger (*Zingiber officinale*) under Sapota-Jatropha-based agroforestry systems	Pandey et al. (2017)
	Navsari	Green gram under *Melia composita*	Bhusara et al. (2018)
	Coastal lowland of Gujarat	Rice-mango	Singh et al. (2017)
	Navsari, Gujarat	Ginger (*Zingiber officinale*) under Sapota-Jatropha-based agroforestry systems	Pandey et al. (2017)
	Navsari, Gujarat, India	Green gram under *Melia composita*	Bhusara et al. (2018)
	Coastal lowland of Gujarat	Rice-mango	Singh et al. (2017)
		Brinjal/okra + mango + teak	
		Sugarcane + teak	
		Grass (*Sorghum spp.*) + sapota	
	Navsari, Gujarat	Mango + sapota + lemon + coriander	Sureshbhai et al. (2017)
		Mango + cabbage	
		Mango + rice	
		Teak + sugarcane	
		Eucalyptus + spider lily	
		Mango + teak + brinjal	
		Teak + Rice	
		Arjun + Nagali	
		Banana with eucalyptus	Agarwal et al. (2017)
		Subabul intercropping with Beans	

(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
		Tobacco/cotton/cabbage with Eucalyptus	
		M. dubia-C. martinii silvimedicinal system	Mohanty et al. (2019)
	Valsad, Gujarat	Mango-banana; mango-maize; mango-sorghum	Bhusara et al. (2016)
	Navsari, Gujarat	Teak-banana; teak-rice	Bhusara et al. (2016)
		Colocasia under palmyra palm	Kazi et al. (2017)
	Odisha, India	*Acacia mangium* in block, field bund and boundary plantation. Intercrops: Pineapple, mango ginger, turmeric and arrowroot	Handa et al. (2019)
		Gmelina arborea-based agrisilvicultural system Pineapple, mango ginger, turmeric and arrowroot	
	Konkan region of Maharashtra, India	Bamboo-based agri-silvicultural system *Dendrocalamus stocksii* and Finger millet	
	Kerala, India	Jackfruit and *Acacia*-based silvihorticultural system *Artocarpus heterophyllus, Acacia auriculiformis, Piper nigrum* is grown on trees	
	Bugel, Yogyakarta	Chillies under coconut	Ruslanjari et al. (2020)
	Claveria, Philippines	Gmelina –maize	Bertomeu et al. (2011)
	Manila, Philippines	Rice under *Cassia spectabilis* and with *Gliricidia sepium*	Maclean et al. (1992)
	Selangor, Malaysia	Grasses and forage legumes under oil palm	Dahlan et al. (1993)
	Leyte Island, Philippines	*Leucaena leucocephala* hedges-cassava	Escalada and Ratilla (1998)
	Gunungkidul, Java, Indonesia	Maize-soybean under *Acacia auriculiformis*	Figyantika et al. (2020)
	West Java	Teak –maize	Khasanah et al. (2015)
Woodlots	Goa, India	*Casuarina* woodlot	Dagar et al. (2014)
	Claveria, Philippines	*Acacia mangium* woodlot	Mercado et al. (2011)
Live fences and hedges	Wayanad, Kerala	Live fencing of *Gliricidia* or *Erythrina*	Kumar (2007)
	Khordha, Odisha	Paddy straw mushroom under coconut plantation	Mohapatra and Chinara (2014)

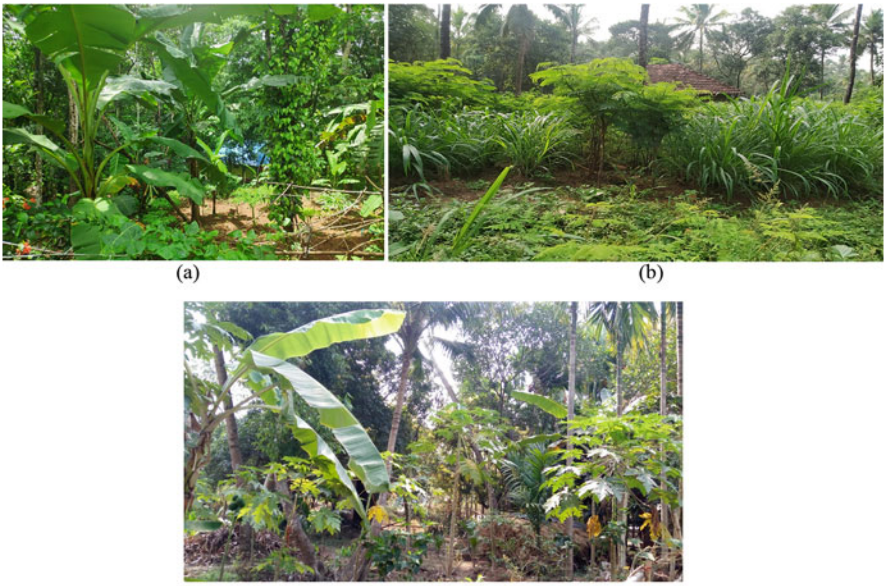
(continued)

Table 14.2 (continued)

Agroforestry practices	Region/country	Agroforestry components	Reference
Multi-enterprise farming systems	Khordha, Odisha	Agrisilvihorticultural system	Monalisa et al. (2020)
	Tirunelveli, Tamil Nadu	*Acacia planifrons* as fallow species on farmland	Jambulingam and Fernandes (1986)
	Ramanathapuram, Tamil Nadu	*Acacia planifrons* as fallow species on farmland	Jambulingam and Fernandes (1986)
	Purba Medinipur (WB)	horti-apiculture, silviapiculture	Dhara et al. (2016)
	North and Middle Andaman, South Andaman, Nicobar	Aquasilviculture	Dagar (1995)
	Andaman and Nicobar	Fish +coconut	Dagar (2000)
		Aqua silviculture	
		Farming in forest	
		Fish behind mangroves	
	Northern Thailand	Fallow enrichment with *Macaranga denticulate*	Yimyam et al. (2003)
	South Sumatra, Indonesia	damar (*Shorea javanica*)-rice-coffee	Mary and Michon (1987)
	Central Java, Indonesia	Maize and cassava with *Melaleuca Leucadendron*	Budiadi et al. (2006)
	Selangor, Malaysia	Ruminants, grasses and forage legumes under oil palm	Dahlan et al. (1993)
	Selangor, Malaysia	Straw mushrooms (*Volvariella volvacea*) on oil palm empty fruit bunches under Dipterocarpus	Kamaliah et al. (2022)
	Malaysia	Sheep rearing in rubber	Tajuddin (1986)
		Honey bees under rubber	
		Rotation poultry under rubber	

(2005) studied the home garden structure across the South Andaman, Middle Andaman and South Andaman and Car Nicobar Islands and categorized them into six types as: (1) arecanut-coconut-rice, (2) arecanut-coconut, (3) coconut-Gliricidia-vanilla, (4) coconut-Gliricidia-black pepper, (5) plantations-vegetables, (6) coconut-tuber.

Home gardens provide meat, milk and egg production, both for household consumption and for sale if livestock is incorporated (Kumar 2007). In addition to creating revenue and employment, home gardens assure the availability of a variety of items such as food, fuel, vegetables, fruits, fodder, spices and medications (Peyre et al. 2006). This ecologically sustainable system has ability to adjust to socioeconomic changes. Home gardens are also providing minerals and nutrients, which can help improve family nutritional security, especially for vulnerable populations.



(a) (b) (c)

Fig. 14.2 (**a**) Typical home garden in Thrissur district, Kerala, India. (**b**) Integration of fodder trees and grasses under home garden in Thrissur, Kerala, India. (**c**) Home gardens of Odisha, India

Year-round availability of varied goods contributes to food security, particularly during 'lean' seasons.

Weersum (1982) identified various tree gardening systems and taungya systems in Java. *Pekarangan* (home gardens), *kebun* or *talun* (forest garden), mixed gardens (*kebun campuran*), intensified taungya in teak and dammar plantations and interplanting of *Pinus merkusii* with beans and potatoes in taungya and intercropping of dryland rice, maize, pepper, peanut and soybean, cassava and potato between alternating rows of direct-seeded teak and *Leucaena leucocephala* were various systems practiced in Java. In west Java, agroforestry system consists of tea and banana in the understory, cloves in the second storey, and *Albizia falcataria, Erythrina* spp., jackfruit, and *Maesopsis eminii* in the top canopy.

Rane et al. (2016) reported that *Dendrocalamus stocksii*, which is frequently found in home gardens and boundaries of farms in Konkan region, could provide revenue of roughly 6000 US$ ha^{-1} $year^{-1}$ from culms in the sixth year and US$ 2130 ha^{-1} $year^{-1}$ from juvenile shoots. Many trials successfully evaluated that many grasses and fodder bank trees can be incorporated in rubber or palm oil plantation of in Andaman-Nicobar Islands, coconut gardens of Kerala to produce fodder as well as improve soil and reduce erosion (Dagar 1995; Raj et al. 2016a, b). Three storeyed multiple cropping system involving *Dipterocarpus* spp., *Pterocarpus dalbergioides, Terminalia catappa*, *Bombax insignis, Lagerstroemia hypoleuca, Artocarpus chaplasha, Albizia lebbeck* and *Canarium euphyllum* at higher canopy, *Erythrina variegata, Ceiba pentandra* and *Areca catechu* as middle storey crops and pineapple as a ground storey crop provides regular economic returns (Dagar 1995; Dagar et al. 2020).

Inclusion of this poultry component in the homegardens is found to be suitable for supplement of farm income. By integration of Japanese quails (*Coturnix japonica*) into the coconut-based mixed farming system, farmer can get additional returns (Subramanian et al. 2000; Venkatesh et al. 2010). Rearing of Russian chinchilla under homesteads of coconut was preliminarily reported to be feasible (Maheswarappa et al. 2000). In coastal Southeast Thailand, houses are surrounded by mixed home gardens, and the extra produce was sold on the local market. In year of crop failure, the cash gain from the sale of palmyra palms compensated for low rice production (Dumrongrojwatthana et al. 2020). One bamboo culm in *kebon tatangkalann* agroforestry system was priced @ US$ 0.6–0.9, while one trunk of mahogany with trunk diameter about 50 cm priced @ US$11.23, 6-year-old tree of *Albizia falcata* with trunk diameter about 20 cm was priced at US$ 4.50 and US$ 5.6 (Parikesit et al. 2005).

14.3.2 Plantation-Based Multi-storied Cropping Systems

The west coast, especially the Western Ghats, hosts many plantation-crops, *viz.,* cashew, coconut, arecanut, rubber and oil palm (Fig. 14.3a). The interspaces of these crops offer opportunity to integrate lower storey and shade tolerant crops (Fig. 14.3b, c). For example, intercropping pineapple (*Ananas comosus*), banana (*Musa* spp.), and cassava (*Manihot esculenta*) in combination with rubber in Kerala (Rajasekharan and Veeraputhran 2002); and turmeric, cassava and banana intercropped with cashew nut, coconut and rubber in Andamans (Dagar 1995) are quite successful. The trees are also used as a support to grow black pepper and betel wine.

Thampan (1996) concluded that intercropping in coconut was of great economic advantage to the small and marginal farmers. In a 50-year-old coconut plantation, cacao was found to be the most ideal mixed crop among several combinations of perennials such as black pepper, cinnamon, clove, nutmeg, coffee, and mulberry. Cacao not only increased yields, but it also increased coconut productivity. In Andaman-Nicobar Islands, coconut and arecanut-based multi-storeyed agroforestry systems are quite common and banana, yams, pineapple, and grasses are cultivated in inter-spaces while black pepper is grown along arecanut palm or Gliricidia as support. Colocasia (*Colocasia esculenta*), greater yam (*Dioscorea alata*) and elephant foot yam (*Amorphophallus campanulatus*) are popular understory crops in coconut gardens (Dagar et al. 2014, 2020). Pine apple along slopes is cultivated quite frequently in all the regions.

Barfod et al. (2015) identified that *Cocus nucifera*, African oil palm (*Elaeis guineensis*), rattan, *Areca catechu*, *Borassus flabellifer, Arenga pinnata* and *Salacca zalacca* are the important palms in agroforestry systems in SE Asia. Palmyra palm in paddy fields provides sugar sap, leaves, wood to a large cottage industry.

(a) (b) (c)

Fig. 14.3 (**a**) Plantation-based multi-storied system (coconut, areca, banana) in Thrissur district, Kerala, India. (**b**) Coconut–arecanut–banana–pepper-based multi-storeyed system in coastal districts of Kerala, India. (**c**) Cultivation of cocoa under coconut plantation in Thrissur, Kerala, India

Plantation-based systems such as coffee, cacao, rubber, oil palm, calamus and Indonesian dammar is integrated with other crops in Southeast Asian nations and islands (Roshetko and Bertomeu 2015). Mango, banana, guava, tomato, coffee, cacao, chilli, turmeric, lemon grass, basil, fragrant screw pine, taro, were mostly cultivated in homegardens of central Sulawesi, Indonesia (Kehlenbeck and Maass 2004).

Coconut plays a significant role in the agrarian economy of India. In the west coast of India, the palm is an essential component in the homestead system of farming. Traditional areas of coconut in India are the states of Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Odisha, Goa, West Bengal, Pondicherry, Maharashtra and Islands of Lakshadweep and Andaman and Nicobar Islands. The coconut palms planted at 7.5 m × 7.5 m apart efficiently consume just 22.3% of land, while the canopy's average air space consumption is approximately 30% and 45–50% of solar radiation is intercepted (Bavappa et al. 1986). Thus, there are possibilities for incorporating appropriate component crops into the interspaces, in order to maximize the use of natural resources. Various shade tolerant crops like Colocasia and shade loving crops like ginger and turmeric successfully intercropped with above plantation crops (Kumar 1994). *Plumbago rosea, Curculigo orchioides, Kaempferia galanga, Maranta arundinacea, Alpinia calcarata, Holostemma annulare, Piper* *longum, Dioscorea spp., Pogostemon cablin,* etc. are suitable intercrops in coconut and other plantations of trees (Nair et al. 1991). Mixing *Morinda citrifolia* in coconut plantation in Konkan region increases coconut yield from 13,300 nuts ha^{-1} in 2008–2009 to 14,387 nuts ha^{-1} in 2012–2013 (Khandekar et al. 2015). This study indicated that integrating various crops with trees increases productivity and profitability.

Thangam et al. (2014) evaluated suitability of 13 varieties of *Heliconia* under coconut (20-year-old) in Goa and found that under coconut (10 m × 10 m) this plant provides income increment of 1760 US$ ha^{-1} in H-4 (Rostrata type) and 1827 US$ ha^{-1} in H-6 (Hybrid type) while other varieties such as Golden Torch (H-2), Hybrid type (H-6), Sexy Pink (H-8) and Wagneriana (H-9) generated total income above 0.1 million rupees by sale of flower and suckers and was recommended as a suitable intercrop in coconut. Basavaraju et al. (2018) reported higher net income in coconut + chrysanthemum (2671 US$ ha^{-1}) while coconut + crossandra, coconut + jasmine, coconut + China aster and coconut + marigold recorded 2391, 2221, 1621 and 1283 US$ ha^{-1}, respectively as compared to sole coconut (722 US$ ha^{-1}). Cultivation of suitable intercrops in plantation crops diversifies and intensifies plantations to increase the productivity and profitability through effective and efficient soil and space utilization. Maheswarappa et al. (2017) studied performance of noni (*Morinda citrifolia*) fruits trees under coconut under and found significantly higher fruit yield (6159 kg ha^{-1} year^{-1}) and the maximum net return of 1448 US$ ha^{-1} and B: C ratio (1.31) when managed with vermicompost + vermiwash+ biofertilizers+ coir pith application.

Under Coastal Maharashtra, net returns of 8545 US$ ha^{-1} from coconut + pineapple + banana + cinnamon was reported as against 2684 US$ ha^{-1} in monocropping. Net returns of 9002 US$ ha^{-1} was reported from coastal Gujarat from coconut + turmeric + elephant foot yam + tannia as compared to 1729 US$ ha^{-1} from coconut monocropping. High density multispecies cropping system has shown to be profitable under Tamil Nadu condition, coconut + cocoa + banana + black pepper could give net returns 4671 US$ ha^{-1} as against 1282 US$ ha^{-1} from cultivation of coconut alone. Under Andhra Pradesh conditions, net return of 3594 US$ ha^{-1} was achieved with a crop combination of coconut + cocoa + pineapple + tomato + elephant foot yam + heliconia, which was significantly greater than the monoculture of coconut (US$ 1045 ha^{-1}) (AICRP (Palms) 2018). Experiment on performance of medicinal and aromatic crops as intercrops in coconut garden under east coast of Andhra Pradesh found that highest net returns were recorded in crop combination coconut + patchouli (1914 US$ ha^{-1}) with benefit-cost ratio of 2.84 followed by coconut + citronella (1450 US$ ha^{-1}) with benefit cost-ratio of 2.12 as compared to the net returns of 395 US$ ha^{-1} with benefit-cost ratio of 1.60 in monocropping of coconut. Farming practice of patchouli followed by citronella as intercrops in coconut could be a source of higher economic return in East Godavari area of coastal Andhra Pradesh (Padma et al. 2018).

Sujatha et al. (2011) studied the economics of intercropping of medicinal plants, e.g., *Vetiveria zizanoides*, *Asparagus racemosus*, *Piper longum*, *Bacopa monnieri*, *Nilgirianthus ciliates*, *Catharanthus roseus*, *Aloe vera*, *Cymbopogon flexuous*, *Cymbopogon martini*, *Ocimum basilicum*, *Pogostemon cablin*, *Artemisia pallens* with arecanut plantations in Dakshina Kannada district and the study implicit that all the combination showed economic benefit in terms of net return per US$ investment having highest in *Cymbopogon flexuous* (4.25) to lowest in *Cymbopogon martini* (1.95). The system productivity with this medicinal crop integration varied from 2990 to 4144 kg ha^{-1} as compared to sole plantation 2795 kg ha^{-1}.

Vishwajith et al. (2015) gave an insight into the feasibility of arecanut-based farming systems among the farming community of coastal Karnataka region and found that the cropping system prevailing could be broadly categorized into sole arecanut, arecanut-banana, arecanut-coco and arecanut-spices groups. Among all these groups arecanut-spices cropping system has better monetary advantages over others. Among the arecanut-spices combination, arecanut-pepper by far is the best one. Among the arecanut-based farming system, inclusion of poultry component has been reported to raise benefit cost ratio from 2.20 (sole arecanut) to 2.72. Growing cocoa with arecanut in North Kanara boosts productivity by roughly 650–-900 kg ha^{-1}. The technique generates net profits of 1.66–1.83 US$ for every $ invested (Bhat et al. 2014). When various flowers cultivated under 40-year-old coconut planted at 10 m × 10 m in Karnataka, jasmine, chrysanthemum, crossandra, China aster and marigold yielded 1045, 4393, 1070, 2158 and 4874 kg ha^{-1}, respectively without affecting growth and yield of coconut (Basavaraju et al. 2018).

Balasimha (2004) obtained yield (kg ha^{-1}) of 2650, 6744, 6496, 10,246, 712 and 3942 for intercropping of Ginger, Greater yam, Elephant foot yam, Tapioca, Sweet potato, Pineapple respectively under arecanut at Palode. Dhanapal et al. (2001) used the Land Equivalent Ratio (LER), Monetary Advantage (MA), Aggressivity Index (A), and Competition Ratio to investigate the benefits of coconut and arecanut-based mixed cropping systems (CR). With an LER of 1.46, the coconut and cacao combination attained a monetary advantage of 199 US$ ha^{-1} year^{-1}. With an LER of 1.41, coconut and turmeric yielded a monetary advantage of 220 US$ ha^{-1} year^{-1}.

Mixing *Morinda citrifolia* in coconut system in Ratnagiri district of Maharashtra gave gross returns of 2493 US$ and B:C ratio of 2.48 and productivity and profitability of coconut when intercropped with *Morinda citrifolia* as compared to sole coconut in a Konkan region of Maharashtra. Coconut yield increased to 14,387 from 13,300 nuts per ha when intercropped with Noni (*Morinda citrifolia*) due to synergetic effect of association (Khandekar et al. 2015). Mixing noni under coconut plantation reported increase in coconut yield from 60 to 74 nuts per palm in 5 years in Gujarat. *Morinda citrifoli*a cropping under coconut increased coconut production as well as the economics of *Morinda citrifolia* as an intercrop revealed that coconut agriculture was more profitable than monocropping (Bhalerao et al. 2016).

Study by Das and Vijaya Kumar (1991) reported 2.18, 1.45 and 1.5 land equivalent ratio (LER) for Arecanut + Cocoa, Arecanut + banana and Arecanut + black pepper respectively. Arecanut-cocoa and arecanut-black pepper mixed cropping provided a monetary benefit of 255 and 245 US$ ha^{-1} year^{-1} under irrigation, respectively. Agroforestry model developed in farmlands of Cauvery delta zone as alley cropping of *Casuarina* with cotton as intercrop had shown higher average net annual income of INR 41,000 (546 US$) when Casuarina attending a total height of 10–12 m and girth at breast height of 26 cm compared with pure casuarina, pure cotton and traditional rice cultivation land use 304 US$, 320 US$ and 433 US$, respectively (Saravanan et al. 2012).

Singh et al. (2017) found that farmers in coastal lowlands of Gujarat mostly preferred mango + rice in AH system, brinjal/okra + mango + teak in ASH system, sugarcane + teak in AH system and grass + sapota in HP system. They also reported 11 trees and 22 agricultural crops in different AGF systems practiced in coastal lowlands of Gujarat. Dobriyal et al. (2019) reported hortisilviculture, agrisilviculture, agrihorticulture, homegardens and hortipasture as common agroforestry system in coastal parts of Gujarat. A study conducted in Valsad district of Gujarat reported higher timber yield (20-year-old teak trees) under teak-rice (43.92 m^3 ha^{-1}) while mango yield obtained was 15.00, 14.82 and 6.57 Mg ha^{-1} under mango + banana, mango + sorghum and mango + maize system (Bhusara et al. 2016), while the total returns was highest in mango + banana (9280 US$ ha^{-1}) followed by mango + sorghum (7935 US$ ha^{-1}).

Sugar palm (*Arenga pinnata*)-based agroforest common in Sulawesi, Java and Kalimantan, has a significant impact on local livelihoods. Different ethnic groups use Aren (*Arenga pinnata*) in different ways, owing to their socioeconomic backgrounds, as well as the availability of other natural resources its uses changes with elevation within an ethnic and cultural setting. It produces delicious fruits and fibres for construction material and domestic utensils, as well as sweet syrup from its flower stalks. Alcoholic beverages, sugar, thatch, and sweets are the four primaries economic aren products. While for weekly revenue, only sugar and alcoholic beverages are gathered. Interestingly, after the global financial crisis of 2008, when the price of rubber fell, several rubber–aren farmers in Batang Toru shifted from sugar to tuak production. Farmers switched to alcohol production to generate alternate livelihood as a result of the decrease in rubber income (Martini et al. 2012).

14.3.3 Silvopastoral Systems

Silvopastoral system refers to land use system in which pasture (grazing land) and livestock production are integrated with woody perennials on the same land management unit. These land use systems are generally characterized by higher productivity on account of the vertical stratification of the shoot and root systems of different components. Growing of nitrogen-fixing trees (Fig. 14.4a) has the added benefit of assisting in the fixation of atmospheric nitrogen into the soil, which is then used by the associated field crops. The interspaces between the coconut are used for growing fodder crops such as guinea grass, BN hybrids (Fig. 14.4b, c) and *Stylosanthes* spp. The results of a field trial conducted by Mathew et al. (1992) in Kerala revealed that growth and yield of fodder species was significantly influenced by tree components only after tree canopy formation. The fodder species such as *Pennisetum purpureum, Panicum maximum, Brachiaria ruziziensis* and *Euchlaena*

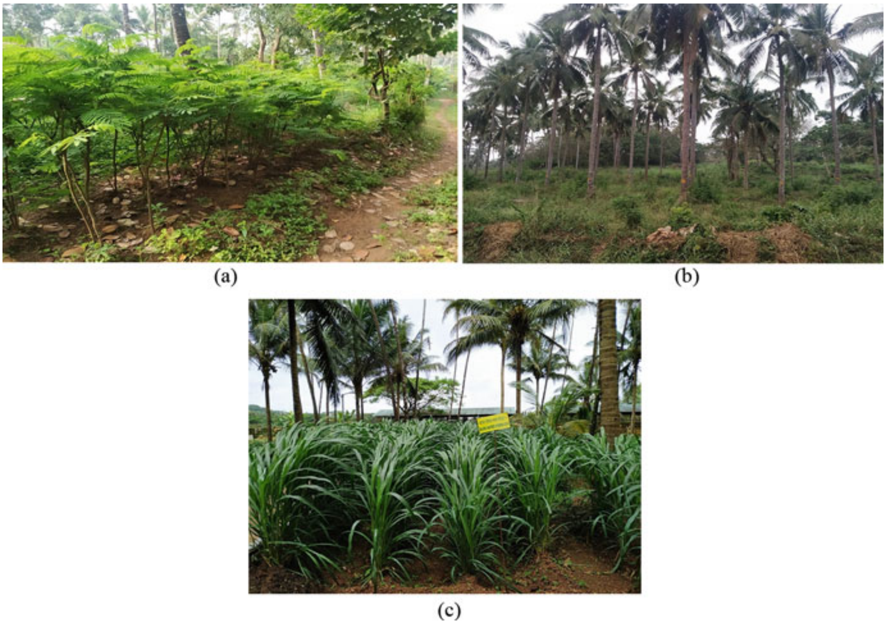


Fig. 14.4 (**a**) Boundary plantation of nitrogen-fixing fodder bank tree (*Calliandra calothyrsus*) around homestead in Thrissur district Kerala. (**b**) Pasture (Guinea grass) under coconut plantation in Thrissur, Kerala. (**c**) Coconut with pasture (Bajra Napier hybrid Co-5) in north Goa district, Goa

mexicana grown in association with *Casuarina equisetifolia* and *Ailanthus malabarica* recorded comparatively higher forage yield even after canopy formation.

Naik et al. (2011) raised fodder maize under 5-year-old cashew plantation in Goa and reported 15.78 tonnes ha^{-1} fresh yield equivalent to 3.63 tonnes ha^{-1} DM. They estimated that if half of Goa's cashew plantation acreage is intercropped with fodder maize, it is possible to produce four million tonnes of fresh fodder (ten million tonnes of DM) in a single crop season which will be sufficient to fulfil the DM need @10.5 kg per animal per day) of the state's entire bovine population for about 3-month period. Multipurpose trees such as *Aegle marmelos, Artocarpus* spp., *Bauhinia variegata, Erythrina variegata, Grewia glabra, Hibiscus tiliaceous, Moringa oleifera, Pitchecelobium dulce, Pongamia pinnata, Samanaea saman, Sesbania grandiflora* and *Trema tomentosa* can be grown in fodder banks (Dagar et al. 2014).

14.3.4 Shelterbelts

Most of the coastal areas are prone to damage caused by cyclones and even Tsunamis. In coastal areas, high winds also carry salt with them and damage crops. Many plants and shrubs, such as *Casuarina equisetifolia, Acacia* *auriculiformis*, and *Gliricidia sepium* may play a vital role in lowering wind speed and protecting crops. These not only protect the crops, but they also aid to improve the soil. Mangroves have extensive root systems that safeguard the shore from the effects of natural calamities. All existing stands must be protected and conserved, and all afforestation plans must be in place to rehabilitate degraded mangrove areas by planting suitable species. Besides mangroves littoral species such as *Pandanus* spp.*, Thespesia populnea, Scaevalia taccada, Tournefortia ovata, Hibiscus tiliaceus,* and *Salvadora persica* may also play important role in protecting the shores and beaches. MPTs such as *Calophyllum inophyllum, Pongamia pinnata, Heriteria littoralis, Terminalia catappa,* and *Manilkara littoralis*, which are found growing luxuriously along beaches of Andamans, may be raised on degraded low-lying areas. These belts protect the shores/beaches, provide valuable forest products and also give shelter to wild life (Dagar et al. 2014).

14.3.5 Farming in Forests

Growing of commercial crops under the shade of trees of natural forests of the Western Ghats of peninsular India is very common (Fig. 14.5). Cardamom hill reserves (CHR) in the high-altitude regions of Kerala constitute a traditional agroforestry system. It involves growing of small cardamom (*Elettaria cardamomum*), a sciophytic commercial crop, under the shade of trees in natural forest. Dominant trees in the evergreen and semi-evergreen forests selectively retained by the growers provide shade to the cardamom crop in this age-old cultural system. Shade trees also vary from place to place depending on local preferences and the silvicultural characteristics of trees.

Fig. 14.5 Cardamom under shade trees in hilly areas of coastal Kerala

Forest farming has been practised in the Andaman and Nicobar Islands for a long time. Young regenerative forest trees are let to grow naturally, or multi-purpose woody perennials are planted at regular intervals. These also support climbers such as black pepper or betel vine. Nutmeg (*Myristica fragrans*), cinnamon (*Cinnamomum verum*), clove (*Syzygium aromaticum*), coffee (*Coffea arabica, C. indica, C. robusta*), and cacao (*Theobroma cacao*) are planted between the retained or planted trees as their root system is not competitive with deep rooted trees. Betel vine and black pepper are planted near trees. *Erythrina variegata, Cieba pentendra, Areca catechu,* and *A. triandia* are frequently used as support trees for climbers in the islands. The interspaces on sloping lands are also used for fruits like pineapple (*Ananas comosus*) but fodder grasses such as *Pennisetum purpureum, Trepsicum laxum, Panicum maximum, Pennisetum polystachion,* and *Setaria anceps* and fodder legumes such as *Stylosanthes guienensis, S. hamata, and Calopogonium mucunoides* are considered more suitable as ground cover to check soil erosion from sloping lands and meet fodder requirements in the islands (Dagar 1995; Dagar et al. 2014, 2020). The Jirikatang Farm of the Department of Agriculture, Andaman and Nicobar Islands is a unique example of forest farming system. The tall forest trees, including commercial timber trees (e.g. *Dipterocarpus* spp., *Pterocarpus dalbergioides, Terminalia* spp., *Bombax insigne, Lagerstroemia hypoleuca, Artocarpus chaplasha, Albizia lebbeck, Canarium euphyllum*, and others) have been retained as canopy with the above-mentioned spice species as middle storey crops, and pineapple or fodder crops as a ground storey crops. Farmers may get economic benefits at regular intervals from this kind of system (Dagar et al. 2014).

14.3.6 Hedge Row Cropping

These practices are usually adopted for sloping lands where forage shrubs are planted across the slope and forage grasses and legumes or crops in the interspaces. *Gliricidia sepium, Leucaena leucocephala, Cassia siamea, Morus alba,* and *Pithecelobium dulce* are trained as hedge row crops. Two parallel rows usually one meter apart of these woody perennials are raised across the slope in close spacing. Further, these rows are repeated leaving 4–6 m wide space for growing intercrops. The hedges are frequently cut at about 1 m height from the ground and the sticks are usually used as fuel wood and foliage as fodder or mulch. In one experiment conducted in high rainfall area (Andamans), *Gliricidia sepium* was established from cuttings of mature plants, which were planted in alleys on a gravely sloping land (across the slope). Four herbaceous fodder species, hybrid napier (*Pennisetum purpurium*), Kazungula (*Setaria anceps*), guinea (*Panicum maximum*) and stylo (*Stylosanthes guianensis*) were raised successfully in interspaces (Dagar and Kumar 1992; Dagar 1995). Commercial trees are also grown along with agricultural crops in order to maximize the net returns from unit area (Fig. 14.6a,b).

Kunhamu et al. (2008) found that best yield of 786 kg ha^{-1} obtained by thinning out 2/3 of *Acacia mangium* growing stock than un-thinned stands gave the lowest

Fig. 14.6 (**a**) *Phoenix acaulis* + Rice traditional agroforestry system in Balasore district, Odisha, India. (**b**) Cashew and *Dendrocalamus stocksii* system at Maharashtra, India

yield (438 kg ha^{-1}) in *A. mangium*- ginger system in Thrissur. Intercropping ginger under *A. mangium* gave higher B:C ratio (3.36–4.26) than compared with sole ginger (2.15) over a 10-year basis in Kerala (Kunhamu et al. 2008). Dalvi et al. (2019) reported that, groundnut outperformed other intercrops in terms of production and returns under mango in the Konkan area of Maharashtra, thus mango + groundnut-based horti-agricultural system may be preferred under rain-fed condition in Konkan region of Maharashtra. Faster growth and higher rhizome output was reported at the 2500 trees ha^{-1} density in 5-year-old *Ailanthus triphysa* when ginger intercropped in between trees as compared to sole ginger (Kumar et al. 2001a, b).

In Krui area of South Sumatra, Indonesia damar (*Shorea javanica*)-rice-coffee agroforests provides wood to meet the villagers' fuel and construction needs, number of food products, contributing to a diversification of the diet and acts as regular revenue by monthly sale of damar resin from *Shorea javanica* trees (Mary and Michon 1987). Bertomeu et al. (2011) reported higher total maize grain yield of 18.06 Mg ha^{-1} and lowest value of 14.48 Mg ha^{-1} when *Gmelina arborea* pruned to retain 20–30% and 60–70% live crown in Gmelina–maize system in Claveria, Philippines while, financial analysis also estimated that retaining 20–30% crown was more profitable. In another study by Bertomeu (2012), *Gmelina arborea* was grown in hedgerows with maize (1 m × 10 m) produces 6–8 m^3 ha^{-1} more merchantable volume than gmelina planted in blocks (2 m × 2.5 m). These studies indicated that intercropping of maize between widely separated tree rows is more profitable and viable for smallholders than either maize monocropping or woodlots, and is thus advised.

Khasanah et al. (2015) analysed teak–maize intercropping in West Java, Indonesia by using tree-crop interactions model (WaNuLCAS) and reported that maximum wood volume is reached at an initial tree density of 625 trees per ha. Martin and van Noordwijk (2009) also simulated intercropping if maize under *Shorea contorta*, *Pterocarpus indicus, Vitex parviflora* and *Swietenia macrophylla* using WaNuLCAS model and reported 50% of the maximum tree biomass still allowing 70% of sole maize yield. Sureshbhai et al. (2017) reported B:C ratio of 3.52 and 2.71 in Teak + Sugarcane system and Mango + Rice system in coastal areas of Gujarat. Mohanty et al. (2019) observed higher essential oil yield, total fresh yield (38.45 Mg ha^{-1}) and dry herbage yield (19.33 Mg ha^{-1}) under *M. dubia* (2 m × 2 m)-*C. martini* system than sole cropping in coastal Gujarat. Study reported that hybrid napier, lemon grass, and stylo produced 21.4, 15.2, and 8.2 Mg ha^{-1} biomass in the initial year under coconut planted at 7.5 m × 7.5 m, respectively (Dagar and Kumar 1992).

Intercrops such as pineapple, banana, vegetables, and yams are raised for the immature phase of perennial crops like natural rubber, whereas coffee, cocoa, and medicinal plants are recommended for the mature phase (Rubber Board 2011). To boost production, the intercrop system makes optimal use of resources. During the non-bearing time of the orchard during the kharif season, intercropping vegetables such as cucumber, ridge guard, bitter guard, snake guard, and sponge guard is also suggested (Gajbhiye et al. 2018). Jessy et al. (2017) reported 3.50 kg m^{-2} yield in Amaranthus and yield of 670 per plant for salad cucumber under rubber in Kerala. Shade tolerant medicinal plants can be easily intercropped under rubber. Jessy et al. (2017) found higher biomass for *Alpinia calcarata* and *Strobiliantis cuspida* produced more biomass and found to be suitable for cultivating in mature rubber plantation. As rubber grows, shade intensified the *Garcinia* perished but vanilla and coffee continued to yield reasonably under rubber in Kerala (Jessy et al. 2017). Plants such as *Gliricidia sepium*, *Vitex trifoliata*, *Lawsonia alba*, *Jatropha gossipifolium*, and Ficus spp. are common in live fences (Dagar 1995). Densely planted *Leucaena leucocephala* at spacing of 50 cm × 50 cm as live fence yielded 23.3 Mg ha^{-1} of dry biomass in 6 cuts in year in AN (Dagar 1995).

Fruit-based agrisilvihorticultural systems with legume intercrops in Odisha were found to be suitable for biomass production and soil moisture conservation. Among the crop combination with fruit trees under different treatments such as mango + cowpea, mango+ groundnut, mango+ blackgram, mango + cowpea, jackfruit + cowpea, jackfruit + groundnut, jackfruit+ blackgram, jackfruit + cowpea, cashewnut + cowpea, cashewnut + groundnut, cashewnut + blackgram, cashewnut + cowpea, intercrops higher soil moisture content was observed with groundnut followed by cowpea, blackgram and cowpea irrespective of fruit tree associated. The highest tree biomass of (7.66 Mg ha^{-1}) was recorded with cashewnut in cashewnut + blackgram system followed by jackfruit in jackfruit + groundnut and jackfruit + blackgram system of (7.06 Mg ha^{-1}) and (6.91 Mg ha^{-1}) at 12 months respectively (Monalisa et al. 2020). Watermelon was cultivated as intercrop in a bio-drained field under *Casuarina equisetifolia* plantation as a potential biodrainage species. The photosynthesis performances of watermelon varieties were higher in the reclaimed field as comparison to controlled field (Roy Chowdhury et al. 2011).

Cashew was initially cultivated as a soil conservation crop on marginal land. However, once its potential was recognized, it was pushed to strengthen the economy, with marginal farmers in the region growing it as commercial plantation crop. With more than 1.7 lakh ha area under cashew plantation in Konkan region and an average productivity of 1378 kg ha^{-1}, it is a proven way to doubling farmers income in coastal areas (Gajbhiye et al. 2018). A 6-year study in coastal Maharashtra reported that a total yield of 4.05 Mg ha^{-1} in Elephant foot yam and 3.63 Mg ha^{-1} in Greater yam was achieved when intercropped under cashew. Elephant foot yam intercropping produced the highest net yields of 4995 US\$ ha^{-1} with a B:C ratio of 4.38, followed by Cashew + Greater yam intercropping with net return of 4335 US\$ ha^{-1} with a B:C ratio of 3.95 (Gajbhiye et al. 2018). Kunhamu et al. (2015) reported higher rhizome yield (7.63 Mg ha^{-1}) of turmeric under mature cashew plantation as compared to open (7.01 Mg ha^{-1}). They also found that galangal yielded 2.95 Mg ha^{-1} under cashew 2.91 Mg ha^{-1} under rubber and 2.15 Mg ha^{-1} under coconut in Thrissur district of Kerala. Pineapple is planted as a biennial crop in Kerala and coastal Karnataka during the first 4–5 years, and farmers find it significantly more profitable than crops like red gram and cassava. Pineapple is the most profitable intercrop in cashew plantation in the early stages of growth. Intercropping in the form of medicinal plants is being used by the Goa Forest Development Corporation (GFDC) to make cashew agriculture more profitable (Visalakshi et al. 2015).

Dendrocalamus stocksii yields 18–24 sticks per clump, with each stick fetching about 1 US\$. Thus, cultivation of bamboo (*D. stocksii*) is a viable way for farmers to doubling their incomes (Rane et al. 2018). It can also easily incorporate in homesteads and farm boundaries. It was reported that the 10-year-old *D. stocksii* plantations provide Net Present Value (NPV) of 4942 US\$ and B: C ratio of 2.99 in coastal Maharashtra (Rane et al. 2018). Subbana and Viswanath (2018) reported economic return of 3043 US\$ $ha^{-1}year^{-1}$ and 2660 US\$ $ha^{-1}year^{-1}$ in block planting of *D. stocksii* and *B. balcoa* in Sindhudurg district of Maharashtra, while B: C ratio obtained was 6.02 and 5.70. Kittur et al. (2016) reported that a spacing of 8 m $\times$ 8 m and 10 m $\times$ 10 m is optimum for intercropping turmeric under *D. strictus* in Thrissur. Study on ginger intercropping under block plantation of *Dendrocalamus brandisii* at 6 m $\times$ 6 m spacing found the highest NPV (net present value) and LEV (land expectation value) which was attributed to low input cost associated with growing bamboo and high market value (Viswanath et al. 2007). Patil et al. (2010) evaluated various field crops under sapota-teak plantation in hilly parts of coastal Karnataka and obtained a B:C ratio of 3.23 and 2.71 for sapota-teak-field crops and sapota-*Lagerstroemia lanceolata*-field crops, respectively after 28 years of establishment.

Casuarina is grown mostly on Tamil Nadu's east coast to suit the needs of the paper industry as well as for the construction of scaffolding poles. After 4 years of cultivation, farmers get a net revenue of INR 83,250 ha^{-1} (1109 US\$ ha^{-1}). A few farmers produce groundnut as an intercrop with casuarina in the first year alone and earn a net profit of INR 40,000 ha^{-1} (533 US\$ ha^{-1}) from groundnut cultivation by harvesting 5 Mg ha^{-1} (Buvaneswaran et al. 2010). Jwel et al. (2019) studied the performance of three grass species, i.e., Guinea (*Megathyrsus maximus*), Thin Napier (*Pennisetum purpureum*) and Setaria (*Setaria glauca*) under three leguminous tree species, i.e., *Acacia mangium*, *Acacia auriculiformis*, *Samanea saman* in coastal rain-fed areas of Odisha. The maximum green forage yield was obtained from Guinea (19.6 Mg ha^{-1}) and *Acacia mangium* showed the best performance with respect to growth parameters. *Acacia mangium* + Guinea system has been reported a benefit cost ratio of 2.8.

Gawankar et al. (2018) reported based on the results from field experiment of intercropping in young oil palm plantation in Konkan region of Maharashtra that banana, pineapple and elephant foot yam when taken as intercrop the net returns were INR 89,549 year^{-1} (1193 US$ year^{-1}) with a B: C ratio 1.83. Performance of field crops intercropping (groundnut, blackgram, greengram and upland paddy) as annual crop components were studied along with the woody perennials- *Eucalyptus tereticornis*, *Casuarina equisetifolia*, *Anacardium occidentale* and *Moringa oleifera* in Cuddalore district in Tamil Nadu. Grain production was found to be the best from the interspaces of *Moringa oleifera* and *Anacardium occidentale*. The lowest yields of field crops were obtained in association with *Eucalyptus tereticornis* (Immanuel and Ganapathy 2010).

Immanuel and Rao (2021) studied the potentiality of groundnut intercropping under Palmyra palm-based agroforestry system in coastal red soils of Tamil Nadu and reported that the palmyra trees up to the density of 567 trees per ha is the optimum population for groundnut intercropping. A mature Palmyra tree produces 125–150 L of sap, from which 20–25 kg of jaggery, 15 kg of palm candy, and non-edible items such as leaves, fibre, and coir can be produced. An average minimum net income of about US$ 20 is earned from one tree. A Palmyra farmer may earn 8000 US$ year^{-1} with a minimum of 400 trees per hectare.

Handa et al. (2019) has given some successful agroforestry models for different agro-ecological regions in India. In the eastern coastal plain, *Gliricidia sepium* and *Leucaena leucocephala*-based silvopastoral system, Guava with *Cenchrus ciliaris*-based hortipastoral system for degraded lands, *Acacia mangium*-based agrisilvicultural system and *Gmelina*-based agrisilvicultural system has been identified as successful models. In the Western Ghats and coastal plains, block planting of Burma bamboo, bamboo-based agrisilvicultural system, jackfruit and acacia-based silvihorticultural system and mulberry and *Calliandra*-based silvopastoral system are identified as successful models. Whereas in islands of Andaman-Nicobar and Lakshadweep coconut-based horti-pastoral system is successful.

14.3.7 Taungya

In the Western Ghats, taungya, a traditional method of developing commercial forest plantations such as *Tectona grandis, Eucalyptus* spp., and *Ailanthus triphysa*, in which agricultural crops are planted on a temporary basis between regularly placed rows of trees, is frequently used. Soil erosion induced by bed preparation for growth of agricultural crops has been the major drawback of taungya and other systems established on sloping lands (Alexander et al. 1980; Moench 1991). In a taungya system involving cultivation of cassava (*Manihot esculenta*) with forest tree *Eucalyptus*, Gopinathan and Sreedharan (1989) reported that 10% substitution of cassava with grass strips reduced soil erosion by 41%.

14.3.8 Woodlots

In recent years agriculture has become more labour-intensive, and private industrial forestry has emerged as a new farming practice. In west and east coast of India woodlots consisting of MPTs are raised to generate more profit with minimal labour inputs. Plantations of *Eucalyptus, Casuarina, Bambusa,* and *Acacia auriculiformis* are quite frequent all along coastal regions (Fig. 14.7). Commercial plantations (woodlots) such as of cashew nut (*Anacardium occidentale*) are quite common near Goa on West Coast and Puri, East Coast. Despite of raising woodlots of MPTs, very limited efforts have been made for systematic studies of these woodlots regarding their bio- mass production and nutrient use efficiency.

14.3.9 Live Fences and Hedges

Live fences and hedges are considered as important agroforestry systems in coastal regions to reduce the soil erosion and enhance soil health. Live fence is planted in single line, double line or zig-zag with trees or shrubs on field boundaries, road side, borders of home gardens, sea shore side or animal enclosures. The choice of species is mostly dependent on nature, size and multiple uses. Majority of the live fences are

Fig. 14.7 Eucalypts woodlot in Puri district, Odisha, India

erected to hinder the movement of wild animals, stray cattle and to provide fodder, fuelwood, mulching material, green manure, etc. These also act as windbreak and modify the microclimate and enrich the soil health. Many trees are found grown on field boundaries, which are used as multipurpose trees by the farmers. Trees like *Acacia* spp, *Ailanthus excelsa*, *Bambusa* spp., *Borassus flabellifer*, *Casuarina equisetifolia*, *Cocos nucifera*, *Carissa carandas*, *Cordia rothii*, *Dalbergia sissoo*, *Ficus* spp., *Leucaena leucocephala*, *Moringa oleifera*, *Prosopis juliflora*, *Syzygium cuminii*, *Tamarindus indica* and *Ziziphus mauritiana* are very frequently found on bunds or farm boundaries. Many of these in association with shrubs are trained as live fences or hedges.

In coastal areas of Gujarat region, *Prosopis juliflora* is commonly trained as protected hedge on farm boundaries along with species of *Agave*, *Capparis* and cactii (*Cactus indicus*, *Cereus peruvianus*, *C. triangularis*, *C. hexagonus*, *Opuntia dillenii*, *O. monocantha*, *O. tuna*). In Odisha coastal region, *Casuarina*, *Pandanus*, and *Acacia auriculiformis* are very common. In many areas of Maharashtra, several plants are grown as live fence and hedges around farms and home gardens such as *Bambusa spp*., *Vitex trifoliata*, *V. negundo*, *Jatropha gossipifolia*, *Ficus rumphii*, *Agave sisalana*, *Erythrina indica, Clerodendrum inerme*, *Duranta repens*, *Erythrina variegata*, *Lawsonia inermis*, *Pithecellobium dulce*, and *Gliricidia sepium*. Bamboo are widely planted species on field boundaries in coastal states due to fast growing nature, favourable climate, local demand and source of income generations. Second largest area of bamboo distributed in coastal states.

In humid conditions of Andamans, *Gliricidia sepium* is widely preferred to plant as hedge row cropping on a gravely sloping land to reduce soil erosion and add lopped material for soil improvement. A hedge row cropping of Gliricidia could produce 5–6 Mg ha^{-1} lopped biomass in first year and increases almost 1.5- to 2-fold after second year onwards (Dagar and Tomar 1998). Another study of Kumar et al. (2005) reported a total 242 Mg ha^{-1} biomass produced by *Bambusa bamboos* grown as hedge-rows from 20 years in Kerala.

14.3.10 Multi-Enterprise Farming Systems

In coastal areas, aqua (shrimp and fish) culture in association with paddy cultivation or in denuded mangrove areas is age-old practice. On the bunds of fish ponds, plants of coconut palm and banana are frequently planted (Fig. 14.8). Many farmers also grow vegetables on dykes of fish ponds. During last two decades, efforts have been made to develop integrated farming systems particularly in waterlogged areas involving fish culture in fishpond, livestock, food and forage crops, vegetables, fruit trees on dykes, poultry/duckery, piggery (if feasible) and plantation crops. Components like horticulture, sericulture, forestry, fish culture, and livestock production have been considered most viable to integrate with annual cropping. For wetland situation, model farming systems have been developed integrating components like fishery and poultry with cropping. To get rid of uncertain yield or very low

Fig. 14.8 Aquaculture along with coconut trees on the bunds at Thrissur, Kerala

yield from the traditional paddy cultivation in coastal saline lands, brackish water fish (*Peneous monodon*) and fresh water fish-like *Tillapia mossambica*, *Mugil passia* and *Mugil tade* have been found most remunerative in situations like West Bengal and Odisha (Dagar et al. 2014).

Tajuddin (1986) studied various integrated rubber smallholders' agroforestry system in Malaysia. They found that rearing sheep in rubber reduces cost of weed control along with meat production with IRR of 44%. The rotational system of broiler production under rubber was determined to be practicable, with a net return on family labour of M$370–M$825 each consignment of 500 birds. The *Apis cerana* species was found to be suitable for honey production, yielding roughly 3 kg per colony every harvest in rubber.

A study on integration of ducks in aqua forestry systems on the six coastal districts of Tamil Nadu (Chennai, Kanchipuram, Thanjavur, Ramanathapuram, Tiruvallur, Villupuram) suggests that under the prevailing geographical conditions ducks were reared from 8 to 15 months in this region as compared to 6–7 months as compared to dry region which was the cause of higher economic return from these systems (Kumaravel 2020).

14.3.11 Agroforestry on Waterlogged Saline Soils (Biodrainage)

The areas lying closer to the sea are flooded regularly with seawater and, therefore, have high salinity and causes waterlogging. Trees species like eucalyptus and casuarina are fast growing and promising biodrainage species. Cramer et al. (1999) showed that *Eucalyptus camaldulensis* intercepted deep ground water while *Casuarina glauca* relied on shallower unsaturated zone. Keeping this fact into consideration Roy Chowdhury et al. (2011) conducted experiments in coastal deltaic Odisha where problem of waterlogging was both due to sea water intrusion and topographical depression. They planted *Casuarina glauca* and *Eucalyptus camaldulensis* at two sites each. Casuarina was found to be more efficient in discharging saline ground water hence was used for bio-drainage plantation at the sites having more salinity in underground water. Under non-saline waterlogged areas Eucalyptus is most useful species as it transpires huge amount of water and lowers down the water table. Jena et al. (2006, 2011) introduced *Acacia mangium* and *C. equisetifolia* with land modifications like excavating ponds for storing excess water and creating soil platforms for raising trees. The growth of trees was far superior and remunerative in modified land configuration and helped in lowering down the water table for growing intercrops.

14.3.12 Mangrove-Based Agroforestry Systems

The Integrated Mangrove Fishery Farming System (IMFS), which involves the development of systems consisting of mangroves, other halophytes (salt-loving plants), and the culture of fish, crab and prawn in ponds or creeks and fruit trees or vegetables on dykes making the coastal aquaculture viable and sustainable (Fig. 14.9). This also opens several possibilities to combine mangrove bio-shield to protect the coast-line from natural disasters like cyclones and livelihood of the

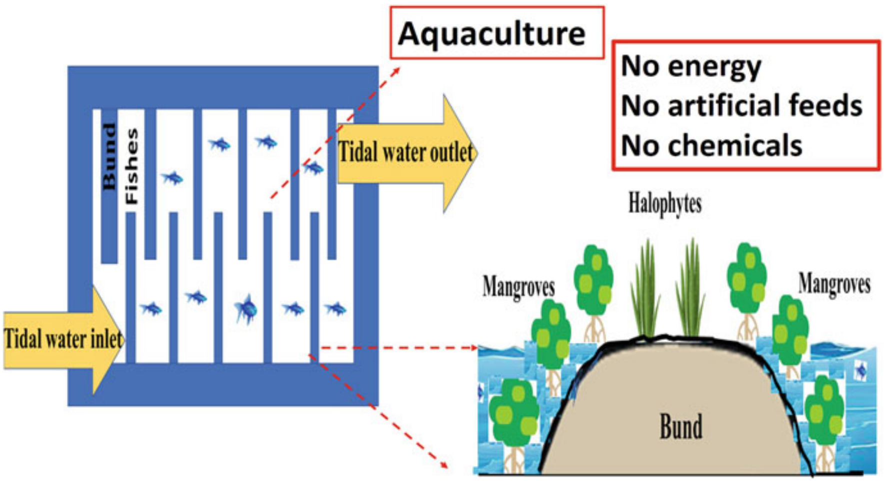


Fig. 14.9 Hypothetical design of seawater-based integrated agro-aqua farming system with inner bunds. (Source: modified and adapted from D'Souza and Ishwar 2012)

coastal population. Many new IMFS models were successfully demonstrated in Pichavaram mangroves, Tamil Nadu by making bunds inside ponds and planting mangroves as per requirement. Due to low and high tide, water is entering and drained out, keeping minimum water level needed for survival of fishes. Proposed IMFS model provides 30–35% area for planting mangroves and halophytes while remaining for holding seawater for farming of fishes or shrimps. *Avicennia* saplings were planted around 2 m land-ward behind *Rhizophora* plantation, in two rows along the sills of bunds. Species of *Avicennia* and *Rhizophora* were planted in a row at 5 m intervals and *Sesuvium portulacastrum* planted on top of bunds. *Lates calcarifer* (sea bass) fish is suitable to integrated in this system (D'Souza and Ishwar 2012). *Rhizophora mucronata*-based agroforestry involving fishes, shrimps and mangrove trees together is being practiced in southeast coast of South Sulawesi, Indonesia (Weinstock 1994). Thus, this is considered most suitable system retaining or raising mangroves in degraded areas.

According to one estimate, the predicted sea-level rise will cause sea water to inundate about 5700 km^2 of land along India's coastline regions. As a result of severe flooding, over seven million coastal families might be directly impacted. Thus, it's necessary to introduce mangroves-based agroforestry in coastal areas and reducing clearance of mangroves in sole fishing or sole cropping. Similarly, most of the coastal areas of South-East Asia are vulnerable to climate change and sea-level rise and need such systems at place. There are many potential mangrove and their associate species such as *Nypa fruticans* (mangrove palm) yielding alcohol, *Pandanus* spp popular for perfumery, coastal almond (*Terminalia catappa*) producing oil-yielding fruits, and multi-purpose tree *Morinda citrifolia* with so many commercial uses, and many other species can be explored for commercial purposes.

14.4 Biodiversity Conservation in Coastal Agroforestry Systems

Since agroforestry is an integrated land-use system, its tree component may open new provisions for both floral and faunal biodiversity conservation, ecosystem services and climate resilience. Agroforestry systems have potential to support as high as 50–80% of biodiversity of comparable to that of the natural system (Noble and Dirzo 1997). The coastal agroforestry harbours rich diversity and the important trees species found grown in different agroforestry systems are listed in Table 14.3.

Agroforestry preserves biodiversity by providing habitat and resources for flora and fauna in deforested and fragmented areas and helps in the preservation of vulnerable and endangered species' germplasm, which may be utilized in the future for crop or tree improvement programmes. It creates connectivity by creating corridors between habitat remnants and forest patches, which may help to maintain the integrity of these fragmented forests and conserve floral and faunal species (Ayyam et al. 2019). Agroforestry systems also play an important role in increasing

Table 14.3 Tree diversity in different agroforestry practices in coastal regions

Agroforestry practices	Associated multi-purpose tree species
Home gardens	*Ailanthus triphysa, Areca catechu, Aegle marmelos, Artocarpus lakoocha, Carica papaya, Annona reticulata, muricata, squamosa, Anacardium occidentale, Azardirachta indica, Areca catechu, Albizia lebbeck, Alstonia scholaris, Artocarpus altilis, gomezianus, heterophyllus, lakoocha, chaplasha, Bauhinia variagata, acuminata, tomentosa, Bambusa balcooa, bambos, nutans, tulda, vulgaris, Carica papaya, Cassia fistula, siamea, Cinnamomum zylanicum, Annona squamosa, Ceiba pentandra, Dipterocarpus grandiflora, Citrus sinensis, Dalbergia latifolia, sissoo, Delonix regia, Erythrina indica, Ficus racemosa, religiosa, Flacourtia inermis, Garcinia indica, gammi-gatta, Gliricidia sepium, Gmelina arborea, Grewia tiliaefolia, Holarrhena pubescens, Hydnocarpus alpina, pentandra, Lannea coromandelica, Mangifera andamanica, indica, Macaranga peltata, Morus indica, Morindo citrifolia, Musa paradisiaca, Manihot esculenta, Murraya konghii, Michelia champaca, Myristica fragrans, Nypa fruiticans, Phyllanthus emblica, Pongamia pinnata, Phoenix sylvestris, Pithecellobium dulce, Psidium guajava, Pterocarpus dalbergioides, Punica granatum, Ricinus communis, Samanea saman, Swietenia macrophylla, Sesbania grandiflora, Syzygium cuminii, aromaticum, Saraca asoca, Schleichera oleosa, Nyctanthes arbortristis, Tectona grandis, Thespesia populnea, Terminalia bellirica, chebula, catappa, procera, Tamarindus indica, Vateria indica, Wrigtia tinctoria, Xylocarpus granatum, Ziziphus mauritiana,* etc.
Shade trees in agroforestry	*Acrocarpus fraxinifolius, Anthocephalus cadamba, Coffea arabica, Eucalyptus* spp., *Gliricidia sepium, Grevillia robusta, Gmelina arborea, Theobroma cacao* and *Michelia champaca* Many forest trees as mentioned above are retained as shade tree Cropping in forest is common practice in many regions
Scattered trees on crop land	*Anacardium occidentale, Areca catechu, Artocarpus heterophyllus, Bambusa balcooa, B. bambos, B. nutans, b. tulda, B. vulgaris, Acacia mangium, Acacia auriculiformis, Ceiba pentandra, Eucalyptus* spp., *Casuarina* spp, *Erythrina indica, Garcinia indica, G. gammi-gatta, Gliricidia sepium, Gmelina arborea, Hevea brasiliensis, Mangifera indica, Melia dubia, dubia, Sapindus mukorossi, Salvadora persica, Santalum album, Tamarindus indica, Morus alba, Musa* spp, and *Tectona grandis*
Windbreaks and shelter-belt plantation	*Casuarina equisetifolia, Acacia auriculiformis*, and *Gliricidia sepium*
Woodlots	*Acrocarpus fraxinifolius, Anthocephalus cadamba, Acacia mangium, Acacia auriculiformis, Erythrina* spp., *Casuarina* spp, *Melia dubia, Leucaena leucocephala* and *Ceiba pentandra*
Silvopasture	*Cocos nucifera, Calliandra calothyrsus, Moringa oleifera, Morus indica, Sesbania grandiflora, Leuceana leucocephala, Salvadora persica, Gliricidia sepium* (Forest trees are also retained frequently)
Live fences or boundary planting	*Ceiba pentandra, Erythrina indica, Jatropha curcus, Vitex negundo, Gliricidia sepium, Morus indica* and *Ricinus communis*
Aqua forestry	*Bambusa balcooa, B. bambos, B. nutans, B. tulda, B. vulgaris, Moringa oleifera, Morinda citrifolia, Cocus nucifera* and *Heritiera littoralis,* many mangrove and associate species

Compiled from different sources

microbial, avian, and faunal diversities. The greater diversity of birds and insect in agroforestry systems provides the beneficial service of pest reduction to adjacent crops (Gillespie et al. 1995; Schultz et al. 2000). It also provides other ecosystem services such as erosion control and water recharge, thereby preventing the degradation and loss of surrounding habitat (Jose 2009).

Gadekar et al. (2020) assessed plant diversity of homegardens in Konkan regions and recorded 88 trees, 48 shrubs, 44 herbs and 26 climber species dominated by Fabaceae, Apocynaceae, Cucurbitaceae, Caesalpiniaceae, Poaceae, Euphorbiaceae, Moraceae and Verbenaceae families of flowering plants. While Peyre et al. (2006) observed 17–51 numbers of plants species on an average in homegardens in Kerala. Chandrashekara and Thasini (2016) surveyed 160 homegardens in Palakkad district of Kerala and found 97 non-crop edible and medicinal plant species belonging to 40 families, out of which, 22 were non-crop edible species, 59 were non-crop medicinal plants and the remaining 16 species were non-crop. The diversity of non-crop edible and medicinal plants has the ability to maintain an ideal balance of ecological and productive properties, as well as to contribute to food and health security in homegardens and rural landscapes. Many of these have potential of domestication as high value crops (Dagar et al. 2014). As a result, there is a need for coordinated measures to foster the exchange of local experiences across rural communities. Singh et al. (2017) reported higher species diversity in homegardens as compared to other systems in coastal lowland of Gujarat.

Kumar et al. (1994) conducted a survey in 17 selected taluks (revenue sub-divisions) among 252 farmers and analysed density, structure, and standing stock of wood in the home gardens of Kerala. They identified 127 woody species in homegardens and mean Simpson's diversity index ranged between 0.251 and 0.739. They found tremendous variability both in number of trees and shrubs present and species diversity of the selected homesteads in different provinces. The mean number of woody taxa found in home gardens ranged from 11 to 39. The floristic diversity was higher in the smaller homesteads and it decreased with increasing size of holdings. Mean Simpson's diversity index ranged from 0.25 to 0.74 (mean value being 0.50) and that of small, medium, and large holdings was 0.61, 0.44, and 0.46, respectively suggesting that floristic diversity was moderate to low compared to a value over 0.90 for the species rich evergreen forests of the Western Ghats. Important tree species in home gardens are *Ailanthus triphysa* (highest frequency), teak (*Tectona grandis*), *Erythrina indica*, and *Bombax ceiba* besides fruit trees such as mango (*Mangifera indica*), jack (*Artocarpus heterophyllus, A. hirsuta*), cashew (*Anacardium occidentale*), *Tamarindus indica, Psidium guajava*, and goose berry (*Emblica officinalis*). Among other MPTs (Table 14.3) *Macaranga peltata*, *Thespesia populnea*, *Gliricidia sepium, Swietenia macrophylla, Casuarina equisetifolia, Leucaena leucocephala, Ceiba pentandra, Annona squamosa, Syzygium cuminii, and Dalbergia latifolia* are important (Dagar et al. 2014).

In Andaman and Nicobar Islands, Dagar (1995) reported 66 species commonly grown in home gardens categorized as vegetables (29 species), fruits (16), pulses (6), nuts/oils (7), spices and condiments (6), and others (2). In a comprehensive study, Pandey et al. (2007) analysed the composition and structure of different components in both Andaman and Nicobar groups of islands. In total, 34 woody plant species are reported to be found in the home gardens of Andaman and 12 in Nicobar that are planted, cared, and harvested. On the basis of cluster analysis, six home garden types namely arecanut-coconut-banana-pineapple, arecanut-coconut-banana-mango, arecanut-coconut-mango-banana, arecanut-coconut-pineapple-banana, coconut-banana-arecanut, and coconut-arecanut-banana are found that correspond the home gardens of South Andaman, North Andaman, Middle Andaman, Little Andaman, Car Nicobar and Nancowry, respectively. Species richness in the Andamans homegardens was higher than in Nicobar. However, diversity was higher and evenness was lower in Nicobar's homegardens (Pandey et al. 2007). The floristic similarity between the homegardens of the Andamans was 82–92%, and it was only 12–18% between the homegardens of Andaman and Nicobar. Spice trees proportion were more common in South Andaman's home gardens, mango and citrus trees in North Andaman, and pineapple and vegetables in Little Andaman (Pandey et al. 2007). In Andaman-Nicobar, an aqua-silviculture method including the creation of a pond behind mangroves is a good way for maintaining and collecting shrimps along with fodder, fuel and other products from mangroves species while without harming mangrove ecology (Dagar 1995; Dagar et al. 2020).

John et al. (2018) studied the biodiversity in agroforestry systems of Lakshadweep Island and recorded total 46 plant species belonging to 24 families, mostly used as mostly useful as vegetable, fibre, medicine, dyes, edible tubers, timbers and for ecosystem services. Unique plants such as highly pungent betel leaf and a large fruited noni (*Morinda citrifolia*), bitter-less *Cucumis melo* also recorded under coconut. Mulukh et al. (2017) identified many indigenous MPTs that incorporated in agroforestry systems by farmers of Ratnagiri district of Maharashtra. They documented *Bambusa arundinacea, Mangifera indica*, *Anacardium occidentale, Tectona grandis, Terminalia tomentosa and Terminalia paniculata*. Palei et al. (2020) investigated the diet of sloth bear in a human modified agroforest landscape of Northern Odisha to improve understanding on its feed resource use and its possible long-term impact on human-sloth bear coexistence. Fruits of *Artocarpus heterophyllus* (jackfruits), *Anacardium occidentale* (cashew), and *Ipomoea batatas* were consumed by sloth bears.

The common species found on other two CHR sites namely Kumili (with 704 trees per ha) and Devikolam (with 700 trees per ha) included *Cullenia exarillata, Palaquium ellipticum, Trema orientalis, Erythrina indica, Mesua nagassarium, Canarium strictum, Macaranga peltata, Artocarpus heterophyllus, A. hirsutus, Ficus hispida, Bischofia javanica, Cedrela toona, Mangifera indica, Myristica dactyloides,* and *Garuga pinnata*. Other species were present occasionally on both or either of the two sites. The evergreen natural forest site at Ayyappancoil recorded a much higher tree density (1976 trees per ha) containing 42 tree species. *Aporusa lindleyana, Hydnocarpus pentandra, Alstonia scholaris, Litsea stocksii, Clerodendron viscosum, Antidesma bunis, Vernonia arborea, Cullenia exarillata, Mesua nagassarium, Holigarna arnottiana, Coreya arborea, Buchanania axillaris, Artocarpus hirsutus, Palaquium ellipticum, Wrightia tinctoria,* and *Vitex altissima* are important tree species found in evergreen natural forests. Presence of heliophilic components (*Aporusa lindleyana, Hydnocarpus pentandra, Alstonia scholaris*, and many others) suggest that these forests are not altogether free from anthropogenic disturbances, and that, in turn, may help the regeneration and survival of such components. The other commercial crops such as cacao (*Theobroma cacao*), coffee (*Coffea* spp.), tea (*Camellia sinensis*) and spices are also cultivated under shade trees (Kumar et al. 1995).

Kumar et al. (1995) compared floristic diversity indices of trees in three CHR and a natural forest in the Western Ghats of Kerala and recorded the highest floristic diversity index for CHRs at Pampadumpara despite having lowest tree density. The floristic spectrum of Pampadumpara site consisted of 40 tree species (522 trees per ha). The trees which showed more than 10% importance value index (IVI) included *Vernonia arborea* with highest IVI (94.6%), followed by *Artocarpus heterophyllus* (46.3%), *Actinodaphne malabarica* (15.9%), *Persea macrantha* (13.6%) and *Erythrina lithosperma* (10.6%). Other common trees at this site included *Cinnamomum malabatrum, Cedrela toona, Prunus ceylanica, Bischofia javanica, Chionanthus malabarica, Macaranga peltata,* and *Mallotus albus.*

The agroforestry systems of Southeast Thailand recorded 27 bird species including the Asian Openbill, Asian Palm Swift and Brahminy Shrike, the Greater Asiatic Yellow bat, and two epiphytic plant species (Dumrongrojwatthana 2017). Clough et al. (2009) recorded bird's diversity in smallholder's cocoa-based agroforest in Central Sulawesi, Indonesia. They recorded about 56 bird's species, out of which one third were endemic to Sulawesi region. They also observed that species richness of frugivores and nectarivores was associated with richness of shade trees in system. Beukema et al. (2007) studied faunal and floral diversity in the Sumatran forest-based agroforestry with primary forest and rubber plantation and reported that the diversity of species in forest-rubber was marginally higher (terrestrial pteridophytes), similar (birds), or lower (epiphytic pteridophytes, trees, and vascular plants as a whole) than in primary forest. In terms of species composition of terrestrial pteridophyte, study discovered that the majority of species present in forest-rubber system (78%) and rubber plantations (75%) were also found in forest plots.

Another study recorded 85 traditional fruit species belonging to 25 families and 41 genera in homegardens of Kampung Lingkungan, Sabah, Malaysia dominated by *Mangifera* spp., *Baccaurea* spp., *Artocarpus* spp., *Averrhoa carambola, Garcinia atroviridis, Nephelium ramboutan-ake, Parkia speciosa* and *Pangium edule*. This tree diversity provides medicine, healthcare, and handicrafts, sustains food and nutrition security along with provides reliable source of revenue for households. Out of recorded species around 79% of species were consumed fresh and 30% cooked into dishes (Salma et al. 2006). Abdoellah et al. (2006) studied floral biodiversity of homegardens in Citarum Watershed of Indonesia and reported Shannon–Wiener diversity index of 1.11 and 2.03 in commercial homegardens and non-commercial homegardens respectively. Jensen (1993) reported 60 plant species excluding weeds with 39 species of important products in homegardens in Java each occupying 0.13 ha area, with 81% cover. Dusun system is an example of integrating a large variety of tree species, many of which are likely components of the original flora, into sustainable land use systems on a tiny, resource-limited island.

This system sustains considerable diversity of trees. The prominent plants in this system were *Syzygium aromaticum*, coconut and nutmeg. A total 147 tree and palm species (at least 10 cm DBH) of 46 families were recorded in *dusun* (forest garden) system, which has been practised for many generations in Saparua island, Central Maluku, Indonesia by Kaya et al. (2002). The alcohol is extracted from the palm sap of *Arenga pinnata* while *Parkia speciosa* and *Mangifera indica* are cultivated for their fruits.

Study of *kebon tatangkalann* agroforestry system of Upper Citarum Watershed, West Java, Indonesia by Parikesit et al. (2005) recorded total of 228 species of varied growth types; however, only 64 of these were classified as trees or bamboos. The typical density of a tree stand was around 1020 mature and juvenile individuals per ha, whereas bamboos was approximately 268 clumps per ha. There were 16 fruit-bearing tree species observed in all tested plots. Fruit trees such *Artocarpus heterophyllus*, *Psidium guajava*, *Mangifera indica* and *Persea americana* were among the most regularly planted in this agroforest. In a survey of 30 homegardens in Central Sulawesi, Indonesia by Kehlenbeck and Maass (2004) recorded around 149 crop species comprising mainly fruits, vegetables, spices or medicinal plants. High biodiversity in this system aids in multiple services. Farmers grow 25 banana varieties, 13 chilli types, and 6 mango, cacao, and sweet potato varieties. Besides cultivating arable crops, 72 ornamental plants and 41 weed species were discovered. However, around half of the weed species were thought to have some therapeutic benefit.

Trees dominated the vegetation in the rattan agroforests of Central Kalimantan, Indonesia, accounting for 79% of the total plants recorded, with 80 different species. Because it took up the most space, *Vitex pubescens* (kaluan) had the highest priority value (Afentina et al. 2020). Kamipang (2015) recorded 62 bird species belonging to 29 families and 20 animal species belonging to 12 groups. Vulnerable species such as the Horsefield's tarsier, sun bear, Sunda clouded leopard and bearded pig can be found in rattan agroforests. The orangutan, ungko or Bornean white-bearded gibbon, and bekantan or proboscis monkey are all endangered species that live in rattan agroforests. Rattan agroforestry demonstrates that rural economic growth does not have to come at the expense of biodiversity protection (Afentina et al. 2020). The stems from *Calamus caesius* and *Calamus trachycoleus* have a high economic value.

Muhamad et al. (2013) studied birds' diversity in agroforest landscapes in West Java and reported 115 bird species from 32 families along with 22 endemic species. Three migratory raptors, 3 swifts and 3 swallows were recorded. Four near-threatened and one endangered (Javan hawk-eagle) were recorded. Study also found species richness of 14.2, Simpson's diversity of 0.89 for mixed tree agroforest. Philpott et al. (2008) reported 105 tree morphospecies and 125 ant morphospecies in coffee plots outside of protected forest and 93 tree morphospecies and 136 ants morphospecies in coffee plots inside protected area.

14.5 Carbon Sequestration in Coastal Agroforestry Systems

Tree provides best opportunity to remove atmospheric CO_2 and store either in wood or soil. The available estimates of carbon stored in tree-based systems (Table 14.4) found ranging from 0.29 to 15.21 Mg C ha^{-1}year^{-1} in above ground and 30–300 Mg C ha^{-1} up to 1 m depth in the soil (Chaturvedi et al. 2016). Viewing ecological benefits of agroforestry such as biodiversity and ecosystem resilience, as well as the potential commercial rewards, extra efforts in carbon farming provide a ‘win-win’ approach for tree-based agroecosystems. Southeast Asia has had the fastest relative increase in total GHG emissions globally between 1990 and 2016 (WRI [World Resources Institute] 2020). Globally, agroforestry has the potential to mitigate between 0.11 and 5.68 Gt CO_2 e year^{-1} (Roe et al. 2019). Agroforestry can help remove 1.57 Gt CO_2 e year^{-1} in ASEAN through afforestation and reforestation, forest management, and peatland restoration (Griscom et al. 2017).

Saha et al. (2009) found that soil carbon content (in 1 m depth) in homegardens of Kerala varies between 101.5 and 127.4 Mg ha^{-1} further they observed that smaller homegardens had higher soil C per unit area (119.3 Mg ha^{-1}) due to higher tree density. C stock was positively correlated to plant diversity in homegardens, thus maintaining high species diversity is good for more C-sequestration. The top soil layer (0–15 cm) of the homegardens had the largest soil organic carbon stocks (15.82 Mg ha^{-1}) followed by the agrihortisilvicultural system (14.56 Mg ha^{-1}) and the agri-silvicultural (12.32 Mg ha^{-1}) reported in Navsari district by Singh et al. (2019). In the humid lowlands of Kerala's Thrissur district, Saha et al. (2010) reported one of the few studies on soil carbon sequestration in coconut stands compared to other common land-use systems such as homegardens, natural forests, rubber plantation, and paddy. SOC content declined in the sequence forest >HGS = rubber ≥HGL ≥coconut > rice paddy up to 1 m deep.

Bhagya et al. (2017) reported 60.93, 56.45 and 53.02 C Mg ha^{-1} of above ground carbon in coconut + *Syzygium cuminii* system, coconut + mango, coconut + *Garcinia* system, respectively, in Kasaragod, Kerala. They also reported that coconut + mango, coconut + jamun (*S. cuminii*), coconut + *Garcini*a and sole coconut system had 82.47, 79.13, 78.69 and 47.06 C Mg ha^{-1}, respectively in below ground soil carbon stock in 0–60 cm soil depth in North Kerala conditions (Bhagya et al. 2017). Approximately, 140.06, 138.91, 131.72 and 98.2 C Mg ha^{-1} of total carbon stored coconut + jamun, coconut + mango systems, coconut + garcinia and sole coconut, respectively (Bhagya et al. 2017). Nutrient management influences carbon sequestration potential of agroforestry. Study by Shinde et al. (2020) at Dapoli, Maharashtra, showed that when 75% recommended dose of fertilizer + 25% of N through organic recycling with vermicompost recorded highest carbon stock of 31.1 Mg ha^{-1} among all treatments, indicating role of integrated nutrient management to enhance C- storage potential. After 2 years, the additional increase in carbon sequestration by palms was 3.01 Mg ha^{-1} under the intercropping system against 2.31 Mg ha^{-1} under the sole cropping (Kumar and Maheswarappa 2019).

Table 14.4 Carbon storage potential of agroforestry practices in coastal regions of SE Asia

Agroforestry practices	System	Region	Age (years)	Spacing/density ha^{-1}	Above ground Mg ha^{-1} $year^{-1}$	Below ground Mg ha^{-1} $year^{-1}$	Total carbon Mg ha^{-1} $year^{-1}$	SOC (depth) Mg ha^{-1} (1 m)	Source
Support system	Black pepper on *Casuarina*	Thrissur, Kerala	22	1111	6.12	0.77	6.89	63.62	Kunhamu et al. (2018)
	Black pepper on *Macaranga peltata*		22	1111	2.83	0.91	3.75	68.64	
	Black pepper on *Ailanthus triphysa*		22	1111	2.68	0.52	3.2	65.56	
	Black pepper on jack		22	1111	4.91	1.19	6.09	64.42	
	Black pepper on *Acacia auriculiformis*		22	1111	5.66	1.37	7.03	71.39	
	Black pepper on *Grevillea robusta*		22	1111	6.35	1.35	7.69	61.26	
Silvopasture	Coconut + *Calliandra*	Thrissur, Kerala	*Calliandra*-5	*Calliandra*-17,777–27,777	1.49–2.06	0.19–0.24	1.68	32.88–64.65	Joy et al. (2019)
			coconut-25	coconut-173	1.32–1.33	–	–		
	Coconut-mulberry	Thrissur, Kerala	Mullberry-3 years	27,777–49,382	1.11–2.12	0.69–1.18	1.18–3.3	90.83–103.43 (40 cm)	John et al. (2019)
			Coconut-25 years	173	1.25–1.3	–	–		
Fodder banks	Hybrid Napier + mulberry (3:2)	Thrissur, Kerala	–	50 × 50 cm	–	–	147.67[a]	107.0	Varsha et al. (2019)
Woodlots	*Acacia auriculiformis* woodlot	Thrissur, Kerala	9	2500	19.11	0.99	20.10	–	Kumar et al. (1998)
	Ailanthus triphysa woodlot		9	2500	2.67	0.41	3.08	–	

(continued)

Table 14.4 (continued)

Agroforestry practices	System	Region	Age (years)	Spacing/ density ha^{-1}	Above ground Mg ha^{-1} $year^{-1}$	Below ground Mg ha^{-1} $year^{-1}$	Total carbon Mg ha^{-1} $year^{-1}$	SOC (depth) Mg ha^{-1} (1 m)	Source
	Artocarpus heterophyllus woodlot		9	2500	5.12	0.56	5.69	–	
	Artocarpus hirsutus woodlot		9	2500	5.12	0.56	5.69	–	
	Casuarina woodlot		9	2500	3.89	0.62	4.51	–	
	Leucaena woodlot		9	2500	1.44	0.18	1.62	–	
	Aonla blocks		9	2500	4.52	0.70	5.22	–	
	Pterocarpus marsupium woodlots		9	2500	4.08	0.41	4.48	–	
	Acacia mangium woodlot		12	625–5000	4.17–8.97	1.37–3.71	5.55–12.68	–	Rocha et al. (2017)
	Grevillea robusta woodlot		21	460	1.49	0.38	1.87	77.56	Thakur et al. (2015)
	Acacia mangium woodlot		6.5	625–5000	5.53–10.22	0.83–2.37	6.37–12.59	27.02–34.54 (15 cm)	Kunhamu et al. (2011)
	Mixed species stand	Thane, Maharashtra	–	–	–	–	–	85.24 (90 cm)	Newaj et al. (2017)
	Acacia mangium woodlot	Odisha	10	2 m × 1 m	–	–	91.30–116.33[a]	–	Routray et al. (2018)
	Mixed-tree lots	West Java	–	1633	108.9[a]	–	–	–	Siarudin et al. (2021)
Home garden	Mixed species homestead garden	Thrissur, Kerala	–	–	–	–	–	103.32–119.3	Saha et al. (2010)

	Multispecies homegardens	Navsari, Gujarat	–	–	–	–	–	31.03 (30 cm)	Singh et al. (2019)
	Tree garden	Lampung, Indonesia	13	628.4	35.3[a]	–	107[a]	60.8 (30 cm)	Roshetko et al. (2002)
	Home garden	Monaragala District, Sri Lanka	–	40–475	8–26[a]	–	–	–	Mattsson et al. (2015)
	Pekarangan	Cisadane watershed, West Java.	–	–	50.08[a]	–	–	–	Filqisthi and Kaswanto (2017)
	Multispecies tree garden	Central Sulawesi, Indonesia	–	–	110.93[a]	83.55[a]	209.39[a]		Wardah et al. (2011)
	Home garden	Bengkulu, Indonesia	–	–	69.5[a]		95.2[a]	25.7	Wiryono et al. (2016)
Plantation crop-based systems	Rubber-based system	Thrissur, Kerala	+50	450–500				119.2	Saha et al. (2010)
	Coconut-based system	Thrissur, Kerala	30	8 m × 8 m				91.7	Saha et al. (2010)
	Coconut (50 years) + *Garcinia indica* (7 yrs.)	Kasaragod, Kerala	Coconut	–	51.14[a]		131.71[a]	18.31 (30 cm)	Bhagya et al. (2017)
			Garcinia	–	1.89[a]				
	Coconut-based integrated system	Ratnagiri, Maharashtra	Coconut (32)	177	28.1–30.4[a]	–	–	0.51–0.77 (30 cm)	Shinde et al. (2020)
			Nutmeg	135	0.59–0.66[a]	-	-	39.4–42.1 (30 cm)	
			Cinnamon	615	–	–	–	32.2–37.4 (30 cm)	

(continued)

Table 14.4 (continued)

Agroforestry practices	System	Region	Age (years)	Spacing/ density ha^{-1}	Above ground Mg ha^{-1} $year^{-1}$	Below ground Mg ha^{-1} $year^{-1}$	Total carbon Mg ha^{-1} $year^{-1}$	SOC (depth) Mg ha^{-1} (1 m)	Source
			Banana	615	–	–	–	29.5–32.1 (30 cm)	
			Pineapple	10,800	–	–	–	28.8–31.6 (30 cm)	
	Arecanut-based mixed cropping	Udupi, Karnataka	–	–	–	–	–	2.38% (30 cm)	Karthika et al. (2019)
	Arecanut + Cocoa	Udupi, Karnataka	–	–	–	–	–	1.9% (30 cm)	
	Cashew + *Stylosanthes scabra* + *Vetiveria zizanioides* (continuous contour trench)	Goa	20	4 m × 4 m	–	–	–	186.3 (90 cm)	Mahajan et al. (2021)
	Oil palm-based farming	Thanjavur, Tamil Nadu	4	140	2.92[a]	0.76[a]	3.68[a]	–	Rakesh et al. (2020)
			8	429	24.94[a]	6.48[a]	31.42[a]	–	
			15	450	62.93[a]	16.36[a]	79.29[a]	–	
	Coconut based	Puthupet, Tamil Nadu		232	–	–	83.3[a]	–	Sundarapandian et al. (2013)
	Cashew based		–	244	–	–	19.5[a]	–	Sundarapandian et al. (2013)
Agrisilviculture	Eucalyptus + Spider lily system (1 m × 1 m)	Navsari, Gujarat	Eucalyptus (6 years)	1600 trees	34.05[a]	8.85[a]	42.90[a]	–	Sureshbhai et al. (2017)
			Spider lily	1 m × 1 m	3.74[a]	1.22[a]	4.97[a]	–	

	Agrihortisilviculture (okra + mango + teak)	Navsari, Gujarat	–	–	–	–	14.56[a]	–	Singh et al. (2019)
	Agrisilviculture (sugarcane + teak)	Navsari, Gujarat	–	–	–	–	12.32[a]	–	
	Mango-based farming	Puthupet, Tamil Nadu	–	204	–	–	70.5[a]	–	Sundarapandian et al. (2013)
	Leucaena leucocephala on shifting cultivation degraded soil (paddy)	Koraput, Odisha	5	1500	–	–	–	14.17–19.63 (20 cm)	Adhikary et al. (2017)
	Gliricidia on shifting cultivation degraded soil (paddy)	Koraput, Odisha	5	1500	–	–	–	14.06–16.58 (20 cm)	
	Black pepper on casuarina	Thrissur, Kerala	22	1111	6.12	0.77	6.89	63.62	Kunhamu et al. (2018)
	Black pepper on *Macaranga peltata*		22	1111	2.83	0.91	3.75	68.64	
	Black pepper on *Ailanthus triphysa*		22	1111	2.68	0.52	3.2	65.56	
	Black pepper on jack		22	1111	4.91	1.19	6.09	64.42	
	Black pepper on *Acacia auriculiformis*		22	1111	5.66	1.37	7.03	71.39	
	Black pepper on *Grevillea robusta*		22	1111	6.35	1.35	7.69	61.26	
	Neolomarkia cadamba + elephant grass *(Pennisetum purpureum)*	West Java		4 m × 2 m	37.0[a]	–	–	–	Siarudin et al. (2021)
	Nelomarkia Caddamba + Cardamom *(Amomum compactum)*			4 m × 2 m	37.0[a]	–	–	–	

(continued)

Table 14.4 (continued)

Agroforestry practices	System	Region	Age (years)	Spacing/density ha^{-1}	Above ground Mg ha^{-1} year^{-1}	Below ground Mg ha^{-1} year^{-1}	Total carbon Mg ha^{-1} year^{-1}	SOC (depth) Mg ha^{-1} (1 m)	Source
	Gmelina arborea + cardamom *(Amomum compactum)*			2 m × 2 m	63.7[a]	–	–	–	
	(Magnolia champaca + cardamom			4 m × 2 m	44.0[a]	–	–	–	
Integrated	Trees + freshwater fishpond	West java	–	704.0	54.00[a]	–	–	–	Siarudin et al. (2021)
	Woody tree species and cocoa	Central Sulawesi, Indonesia	–	–	98.46[a]	42.42[a]	125.97[a]		Wardah et al. (2011)

[a] Unit of carbon stored is in Mg ha^{-1}

Roshetko et al. (2002) projected that time-averaged above-ground C stocks of home garden systems range between 30 and 123 Mg C ha^{-1}. According to a field trail conducted in Lampung, Indonesia, 13-year-old home gardens stored 35.3 Mg C ha^{-1} in their above-ground biomass, which was comparable to C stocks found in similar-aged nearby secondary forests. They also stated that C sequestration potential would be around 80 Mg C ha^{-1}, if homegardens or other agroforestry systems expanded on currently degraded and underused areas of *Imperata* grasslands. Leuschner et al. (2013) reported 19 Mg C ha^{-1}, 20 Mg (DM) ha^{-1} year^{-1} and 78 Mg C ha^{-1} of above ground biomass, belowground biomass and SOC pool (2.5 m depth), respectively in cocoa agroforestry in Sulawesi, Indonesia.

14.6 Coastal Agroforestry Vis-à-Vis Sustainable Development Goals

By adopting agroforestry, it is possible to achieve at least nine out of the 17 sustainable development goals (SDG): poverty reduction (SDG:1), hunger alleviation (SDG:2), health (SDG:3), improving gender equality (SDG:5), increasing access to clean water (SDG:6), sustainable energy solutions (SDG:7), responsible agricultural production (SDG:12), climate change action (SDG:13), and biodiversity conservation and sustainable land management under SDG:15 (Fig. 14.10).

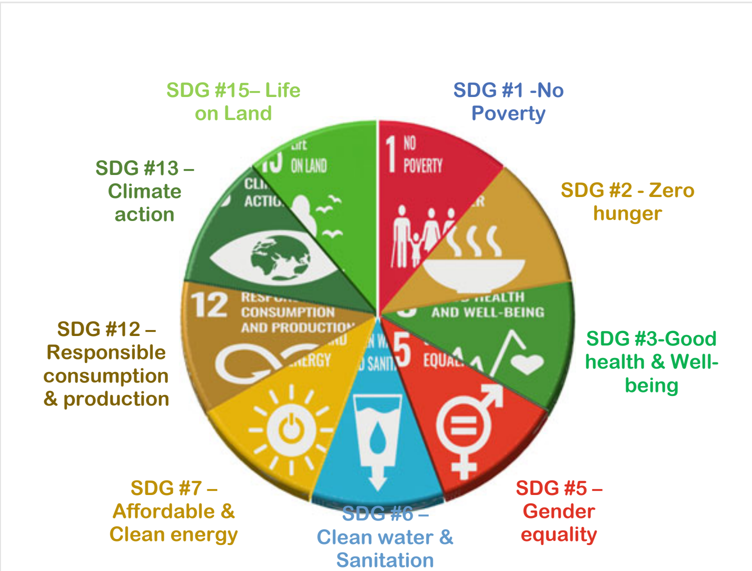


Fig. 14.10 Role of agroforestry in meeting sustainable development goals

SDG #1: No Poverty

Diversification through integrating trees in agriculture unlocks the treasure to provide multifunctional benefits of 6fs, viz., food, fruit, fuel, fibre, fodder and fertilizers. Diversification of system reducing agricultural inputs and thus production costs, or by increasing productivity, agroforestry can increase household income, particularly through homegardens.

SDG #2: Zero Hunger

Food and monetary returns are provided by coastal agroforestry systems, which include tree leaves for vegetable and fodder, fruits and seeds for food, tiny branches for burning wood, and lumber for sale. Fruits, vegetables, and medicinal/ornamental plants are all available from home gardens. People's livelihoods are inextricably linked to agroforestry. Agroforestry trees provide raw materials to a range of industries. Agroforestry offers farmers with year-round work since it requires input throughout the year (Newaj et al. 2018).

SDG #3: Good Health and Well-Being

The ecosystems health directly or indirectly determines human well-being. Agroforestry provides to greater access to a variety of healthy foods, medication supply, clean air, and heat stress reduction. Polluted particles are filtered from the airstreams by tree rows (dust, gas, and microbial constituents). The nitrogenous fertilizers that leach into irrigation water are filtered by the tree roots' safety net. Many trees such as *Moringa olefera, Tamarindus indica, Morinda citrifolia* and *Cocos nucifera* and vegetables and tropical fruits are rich source of minerals and nutrients.

SDG #5: Gender Equality

Throughout the world approx. three billion people depends on firewood for cooking and hot water. In this, women are the main collectors of fuelwood and it bring drudgery and health issues. The study from India states that almost 374 h per year are spent by women for collection of firewood. Growing trees in farm provides easy access to firewood and diverting time to productive purposes. However, women are involved in many agroforestry practices from planting to utilizing tree products and income for household purposes.

SDG #6: Clean Water and Sanitation

Water is probably the most vital resource for our survival. The inherent capacity of trees offers hydrological regulation as evapotranspiration recharge atmospheric moisture for rainfall; enhanced soil infiltration recharges groundwater; obstructs sediment flow; rainwater filtration reduces heavy metals deposits (Ellison et al. 2017). Extensive studies of Herrera et al. (2017) in 35 nations concludes that 30 present more tree cover in watershed results improved sanitization and reduced child mortalities through diarrheal and other related diseases.

SDG #7: Affordable and Clean Energy

Wood fuels are only source of energy to billions of poverty-stricken people. Though trees in farmland are a substitute for natural forest, renewable in nature and also modern technologies in the form of biofuels, ethanol, electricity generation and dendrolignocellulosic biomass sources are truly affordable and clean. Ideal agroforestry models possess trees which are fast-growing, high coppicing, of higher calorific value, and short rotation of (2–3 years) and provide biomass of 200–400 Mg ha^{-1} at minimum input on degraded lands with other several indirect benefits.

SDG #12: Responsible Consumption and Production
Agroforestry is a sustainable land management strategy to diversify production through efficient use of natural resources. The production of agricultural and wood-based commodities on a sustainable basis without depleting natural resources as low as external inputs (chemical fertilizers and pesticides) reduces the ecological footprints.

SDG #13: Climate Action
Globally agricultural production and on-going land-use changes account for up to 24% GHG emission from ~22.2 million km^2 of agricultural area. Under this, agroforestry is a low-hanging fruit, which provides adaptation and mitigation measures. The studies depict that conversion of agricultural land to agroforestry land-use sequesters about 27.2 ± 13.5 tons CO_2 eq per year per ha after the establishment of systems. ICAR-CAFRI, Jhansi estimated that tree on farmland could sequester 109.34 million tons CO_2eq annually from 15.31 m ha that offset about 33% of the total emissions from agriculture of India (www.cafri.com).

SDG #15: Life on Land
Agroforestry 'mimic's forest ecosystem' and contributes conservation of wildlife natural habitats, corridors between habitat and diversified landscape. Delivery of ecosystem services of trees regulates life on land. As discussed earlier, the tropical home garden consists of species richness from 27 (Sri Lanka) to 602 (Java).

14.7 Conclusions

The changing climate is adversely affecting mankind and the environment. In some of the coastal cities, rising sea levels have already forced people to migrate towards new and safer places. Apart from this, other natural adversities, such as higher incidence of erratic rainfall, droughts, cyclones etc., are debiting billions of dollars from the national exchequers. To overcome these challenges posed by climate change, adaptation and mitigation strategies are vital. Practising agroforestry is one of the solutions, which besides insuring against the climate vagaries, also brings assured additional income and sustainability to the system. The agroforestry is a diverse system that mimics the forest and creates equal importance to all the components. The main premise of agricultural intensification through agroforestry are adaptability, productivity and sustainability. Each agroforestry system has its own identity and purpose. Home gardens are the best examples of biodiversity conservation and livelihood security, while shelterbelts sacrifice themselves to safeguard others. Plantation crop-based systems explain the complementary lifestyle to achieve higher income with efficient natural resource utilization. The ecosystem services generated by agroforestry are often innumerable and unaccountable. Agroforestry is the future of farming on the planet earth, and the adoption of agroforestry helps to achieve nine out of 17 SDG goals. Small and marginal farmers in coastal areas are benefitted from agroforestry because it preserves biodiversity while also providing food, nutrition, and income security. It is evident that agroforestry can act as a store house of biodiversity compared to monoculture. Agroforestry has many times, and nature tested models in its basket. Scientific diagnosing and designing will help identify suitable agroforestry models for coastal and island ecosystems, which will also pave the way towards biodiversity conservation and livelihood security. In coastal regions, there is a need for focused research on understanding traditional agroforestry systems, documenting floral and faunal biodiversity, domestication of valuable and less known multipurpose tree species, value addition, ecosystem services and socio-economic impact analysis.

References

Abdoellah OS, Hadikusumah HY, Takeuchi K, Okubo S (2006) Commercialization of homegardens in an Indonesian village: vegetation composition and functional changes. Agrofor Syst 68:1–13

Adhikary PP, Hombegowda HC, Barman D, Jakhar P, Madhu M (2017) Soil erosion control and carbon sequestration in shifting cultivated degraded highlands of eastern India: performance of two contour hedgerow systems. Agrofor Syst 91(4):757–771

Afentina, McShane P, Wright W (2020) Ethnobotany, rattan agroforestry, and conservation of ecosystem services in Central Kalimantan, Indonesia. Agrofor Syst 94(2):639–650

Agarwal NK, Shukla OP, Narkhede SL, Chauhan SKS (2017) Promotion of short rotation agro and farm forestry system in Gujarat and Maharashtra by JK paper limited unit-CPM. Indian For 143(9):862–868

AICRP (Palms) (2018) Annual Report 2017-18. In: Maheswarappa HP, Sajan JV (eds) ICAR-all india co-ordinated research project on palms. ICAR-CPCRI, Kasaragod, p 144

Alavalapati JRR, Luckert MK, Gill DS (1995) Adoption of agroforestry practices: a case study from Andhra Pradesh, India. Agrofor Syst 32(1):1–14

Alexander TG, Sobhana K, Balagopalan M, Mary MV (1980) Taungya in relation to soil properties, soil depreciation and soil management. KFRI Reserch Report No. 9. Kerala Forest Research Institute, Peechi, p 24

Apshara SE (2013) Performance of selected cocoa (*Theobroma cacao* L.) clones under arecanut and coconut. J Plant Crops 41(2):242–246

Arunachalam V, Reddy DVS (2007) Foliar traits of jasmine plants intercropped in coconut. Agrofor Syst 71(1):19–23

Ayyam V, Palanivel S, Chandrakasan S (2019) Agroforestry for livelihood and biodiversity conservation. In: Coastal ecosystems of the tropics—adaptive management. Springer, Singapore. https://doi.org/10.1007/978-981-13-8926-9_16

Balasimha D (2004) Cropping systems. In: Balasimha D, Rajagopal V (eds) Arecanut. CPCRI, Kasaragod, pp 103–130

Barfod AS, Balhara M, Dransfield J, Balslev H (2015) SE Asian palms for agroforestry and home gardens. Forests 6(12):4607–4616

Basavaraju TB, Prashanth M, Maheswarappa HP (2018) Performance of flower crops as intercrops in coconut garden in southern dry region of Karnataka. J Plant Crops 46(1):52–56

Basic Statistics (2001) Andaman and Nicobar Islands: basic statistics. Directorate of Economics and Statistics, Andaman and Nicobar Administration, Port Blair, p 461

Bavappa KVA, Abdul Khader KB, Biddappa CC, Khan HH, Kasturi Bai KV, Amadasan A, Sundaragu P, Bopaiah BM, Thomas GV, Misra LP, Balasimha D, Bhat NT, Bhat SK (1986) Coconut and arecanut based high density multi-species cropping systems. J Plant Crops 14(2): 74–87

Bertomeu M (2012) Growth and yield of maize and timber trees in smallholder agroforestry systems in Claveria, northern Mindanao, Philippines. Agrofor Syst 84(1):73–87

Bertomeu M, Roshetko JM, Rahayu S (2011) Optimum pruning intensity for reducing crop suppression in a Gmelina–maize smallholder agroforestry system in Claveria, Philippines. Agrofor Syst 83(2):167–180

Beukema H, Danielsen F, Vincent G, Hardiwinoto S, van Andel J (2007) Plant and bird diversity in rubber agroforests in the lowlands of Sumatra, Indonesia. Agrofor Syst 70(3):217–242

Bhagya HP, Maheswarappa HP, Surekha RB (2017) Carbon sequestration potential in coconut-based cropping systems. Indian J Hortic 74(1):1–5

Bhalerao PP, Maheshwarappa HP, Patil SJ (2016) Evaluation of Noni (*Morinda citrofolia*) as a mixed crop in coconut garden under South Gujarat condition. Curr Hortic 4(1):52–54

Bhat R, Sujatha S, Chowdappa P (2014) Arecanut-based cropping system fetches more return. Technology 7:111–126

Bhusara JB, Thakur NS, Hegde HT (2016) Bio-economic appraisal of traditional agroforestry systems prevalent in Valsad district, Gujarat. J Tree Sci 35(2):7–14

Bhusara JB, Dobriyal MJ, Thakur NS, Sondarva RL, Prajapati DH (2018) Growth and yield performance of green gram under *Melia composita* plantations. J Pharmacogn Phytochem 7(3):1490–1494

Budiadi KY, Ishii HT, Sabarnurdin MS, Suryanto P, Kanazawa Y (2006) Biomass cycling and soil properties in an agroforestry-based plantation system of kayu putih (*Melaleuca leucadendron* LINN) in East Java, Indonesia. Agroforest Syst 67(2):135–145

Buvaneswaran C, Saravanan S, Jayaraj RSC (2010) Economics of cultivation of important trees in farmlands in Tamil Nadu. Indian Journal of Agroforestry 12(1):53–58

Campbell J, Whittingham E, Townsley P (2006) Responding to coastal poverty: should we be doing things differently or doing different things. Environment and livelihoods in tropical coastal zones. CABI, Wallingford, pp 274–292

Census of India (2011) Report on post enumeration survey. Registrar General & Census Commissioner, GoI, New Delhi

Chandrashekara UM, Thasini VM (2016) Non-crop edible plants and medicinal plants in Homegarden Agroforestry System of Palakkad District, Kerala. Int J Ecol Environ Sci 42(2): 183–191

Chaturvedi OP, Handa AK, Kaushal R, Uthappa AR, Sarvade S, Panwar P (2016) Biomass production and carbon sequestration through agroforestry. Range Manag Agrofor 37(2): 116–127

Clough Y, Putra DD, Pitopang R, Tscharntke T (2009) Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. Biol Conserv 142(5):1032–1041

Cramer VA, Thorburn PJ, Fraser GW (1999) Transpiration and groundwater uptake from farm forest plots of *Casuarina glauca* and *Eucalyptus camaldulensis* in saline areas of southeast Queensland, Australia. Agric Water Manag 39(2–3):187–204

D'Souza N, Ishwar NM (2012) Coastal sustainability: learnings from MFF (India) projects. IUCN India Country Office, New Delhi, p 32

Dagar JC (1991) Agroforestry practices for coastal Bay Islands. J Indian Soc Coastal Agril Res 9: 433–439

Dagar JC (1994) Strategies for sustainable use of Island resources of India. J Indian Soc Coastal Agril Res 12:187–191

Dagar JC (1995) Agroforestry systems for Andaman and Nicobar Islands in India. Int Tree Crops J 8(2 & 3):107–128

Dagar JC (1996) Rehabilation of Coastal saline lands by planting with suitable species. J Indian Soc Coastal Agric Res 14:185–191

Dagar JC (2000) Agroforestry systems for coastal and island regions. Indian J Agrofor 2:59–74

Dagar JC, Kumar V (1992) Agroforestry in Bay Islands. Indian For 118:411–415

Dagar JC, Minhas PS (2016) Agroforestry to rehabilitate the Indian coastal saline areas. In: Dagar J, Minhas P (eds) Agroforestry for the management of waterlogged saline soils and poor-quality waters. Advances in agroforestry, vol 13. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2659-8_8

Dagar JC, Tomar OS (1998) Suitable agroforestry systems for coastal saline regions: case study. J Range Manage Agrofor 19:165–172

Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Agroforestry systems in india: livelihood security & ecosystem services. Springer, New Delhi, pp 185–232

Dagar JC, Gangaiah B, Gupta SR (2020) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 2. Springer, Singapore, pp 367–424. https://doi.org/10.1007/978-981-15-4136-0_13

Dahlan I, Yamada Y, Mahyuddin MD (1993) Botanical composition and models of metabolizable energy availability from undergrowth in oil palm plantations for ruminant production. Agrofor Syst 24(3):233–246

Dalvi VV, Meshram NA, Shigwan AS, Rane AD, Patil VK, Burondkar MM, Tripathi VD, Gawali AS (2019) Performance of agricultural crops under mango based horti-agricultural system in Konkan. Adv Agric Res Technol J 3(2):216–219

Das PK, Vijaya Kumar K (1991) Evaluation of LER and advantages in coconut/arecanut based systems. J Plant Crops 18:356–358

Dhanapal R, Subramanian P, Sairam CV, Thampan C (2001) Farmer's experience and feasibility of mixed cropping of arecanut in coconut garden. J Plant Crops 29(3):42–45

Dhara PK, Panda S, Sarkar S, Das NC (2016) Agroforestry systems practised in new alluvial zone of West Bengal. In: Acharya SK, Basu D, Das JK, Adhikary MM, Mishra C (eds) Proceeding of international conference on agriculture, food science, natural resource management and environment dynamics: people, technology and sustainable development. Krishi Sanskriti Publication, Delhi, pp 162–164

Dixon RK (1995) Agroforestry systems: sources or sinks of greenhouse gases? Agrofor Syst 31(2): 99–116

Dobriyal MJ, Husain M, Prajapati VM, Devanand J (2019) Agroforestry models of South Gujarat. Flora Fauna 25(2):137–139

Duffy C, Pede V, Toth G, Kilcline K, O'Donoghue C, Ryan M, Spillane C (2021) Drivers of household and agricultural adaptation to climate change in Vietnam. Climate Dev 13(3): 242–255

Dumrongrojwatthana P (2017) Participatory modelling to improve understanding of land use change and adaptive management capacity: case study of Sathing Phra district, Songkhla province. Final report (Thailand Research Fund: TRG5880219)

Dumrongrojwatthana P, Wanich K, Trébuil G (2020) Driving factors and impact of land-use change in a fragile rainfed lowland rice-sugar palm cultural agroforestry system in southern Thailand. Sustain Sci 15:1317–1335. https://doi.org/10.1007/s11625-020-00819-5

Ellison D, Morris CE, Locatelli B, Sheil D, Cohen J, Murdiyarso D, Gutierrez V, Van Noordwijk M, Creed IF, Pokorny J, Gaveau D (2017) Trees, forests and water: cool insights for a hot world. Glob Environ Change 43(2017):51–61

Escalada RG, Ratilla BC (1998) Effects of Leucaena biomass application in conjunction with fertilizers on cassava and taro yields in the Philippines. Agrofor Syst 41(3):251–266

FAO [Food and Agriculture Organization of the United Nations] (2015) FAO statistical pocketbook 2015. Food and Agriculture Organization, Rome

FAO [Food and Agriculture Organization of the United Nations] (2021) State and outlook of agroforestry in ASEAN: status, trends and outlook 2030 and beyond. In: Lin T, Catacutan DC, van Noordwijk M, Mulia R, Simelton E, Quang Tan Nguyen, Finlayson RF, Rogel CN, Orencio P (eds). Bangkok, Thailand: Food and Agriculture Organization of the United Nations; Bogor, Indonesia: World Agroforestry (ICRAF); CGIAR Research Program on Forests, Trees and Agroforestry. Los Baños, Philippines: Southeast Asian Regional Center for Graduate Study and Research in Agriculture; Jakarta, Indonesia: ASEAN Secretariat

Figyantika A, Mendham DS, Hardie MA (2020) Productivity benefits from integrating *Acacia auriculiformis* and agricultural cropping in Java, Indonesia. Agrofor Syst 94:2109–2123

Filqisthi TA, Kaswanto RL (2017) Carbon stock and plants biodiversity of pekarangan in Cisadane watershed West Java. In: IOP conference series: earth and environmental science, vol 54(1). IOP Publishing, p 012024

Gadekar KP, Godbold DL, Patel RA (2020) Floral diversity of traditional agroforestry homegardens in Konkan coast of Maharashtra, India. Indian J Agrofor 22(1):78–83

Gajbhiye RC, Gavit R, Salvi BR, Varadkar RS, Patil VK, Rane AD, Dosani AAK, Haldankar PM, Bhattacharyya T (2018) Cashworthy companion of Konkan farmers: Cashewnut. Adv Agric Res Technol J 2(2):175–184

Gawankar MS, Haldankar PM, Salvi BR, Haldavanekar PC, Malshe KV, Maheswarappa HP (2018) Intercropping in young oil palm plantation under Konkan Region of Maharastra, India. Int J Curr Microbiol App Sci 7(12):2752–2761

Gillespie AR, Miller BK, Johnson KD (1995) Effects of ground cover on tree survival and growth in filter strips of the corn belt region of the Midwestern U.S. Agric Ecosyst Environ 53:263–270

Gopinathan R, Sreedharan C (1989) Soil erosion as influenced by rainfall erosivity under different agroforestry systems. In: Reifsnyder WS, Darnhofer TO (eds) Meteorology and agroforestry: proceedings international workshop on the application of meteorology to agroforestry systems planning and management. International Centre for Agroforestry, Nairobi, pp 407–418

Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, Schlesinger WH, Shoch D, Siikamaki JV, Smith P, Woodbury P, Zganjar C, Blackman A, Campari J, Conant RT, Delgado C, Elias P, Gopalakrishna T, Hamsik MR, Herrero M, Kiesecker J, Landis E, Laestadius L, Leavitt SM, Minnemeyer S, Polasky S, Potapov P, Putz FE, Sanderman J, Silvius M, Wollenberg E, Fargione J (2017) Natural climate solutions. Proc Natl Acad Sci U S A 114:11645–11650

Hallegate S, Green C, Nicholls RJ, Corfee-Morlot J (2013) Future flood losses in major coastal cities. Nat Clim Chang 3:802–806

Handa AK, Dev I, Rizvi RH, Kumar N, Ram A, Kumar D, Kumar A, Bhaskar S, Dhyani SK, Rizvi J (eds) (2019) Successful agroforestry models for different agro-ecological regions in India. Central Agroforestry Research Institute, Jhansi and ICRAF-South Asia Regional Programme, New Delhi

Herrera D, Ellis A, Fisher B (2017) Upstream watershed condition predicts rural children's health across 35 developing countries. Nat Commun 8:811

Hinkel J, Nicholls RJ, Tol RSJ, Wang ZB, Hamilton JM, Boot G, Vafeidis AT, McFadden L, Ganopolski A, Klein RJT (2013) A global analysis of erosion of sandy beaches and sea-level rise: an application of diva. Glob Planet Chang 111:150–158

Immanuel RR, Ganapathy M (2010) Performance of field crops along with four tree species in coastal Tamil Nadu. Indian J For 33(1):67–70

Immanuel RR, Rao GB (2021) Production potential of groundnut under palmyra (*Borassus flabellifer*) based agroforestry system in coastal red soils of Tamil Nadu. Crop Res 56(3-4): 105–110

ISFR [India State of Forest Report] (2013) Forest Survey of India, Ministry of Environment & Forests, Government of India, pp 1–252

Jaisankar I, Singh AK, Velmurugan A, Samadder A (2017) Effect of Shade on Noni (*Morinda citrifolia* L.) under Bay Island conditions. J Andaman Sci Assoc 22(1):25–29

Jambulingam R, Fernandes ECM (1986) Multipurpose trees and shrubs on farmlands in Tamil Nadu State (India). Agrofor Syst 4(1):17–32

Jena SK, Sahoo N, Roy Chowdhury S, Mohanty RK, Kundu DK, Mohanty M (2006) Optimizing microwater resource design and integrated farming system approach for enhancing productivity of waterlogged areas. J Indian Coastal Agric Res 24(1):184–187

Jena SK, Sahoo N, Roy Chowdhury S, Mohanty RK, Kundu DK, Behera MS, Kumar A (2011) Reclamation ofcoastal waterlogged wasteland through biodrainage. J Indian Coastal Agric Res 29:57–62

Jensen M (1993) Soil conditions, vegetation structure and biomass of a Javanese homegarden. Agrofor Syst 24(2):171–186

Jessy MD, Joseph P, George S (2017) Possibilities of diverse rubber-based agroforestry systems for smallholdings in India. Agrofor Syst 91(3):515–526

John KJ, Nair RA, Suma A, Unnikrishnan M, Arunachalam V (2018) Agro-biodiversity and ethnobotany of Lakshadweep Islands of India. Genet Resour Crop Evol 65(8):2083–2094

John AR, Raj AK, Kunhamu TK, Anoop EV, Jamaludheen V (2019) Forage yield and carbon dynamics of mulberry fodder banks under varying density and harvest interval in coconut garden. Indian J Agrofor 21(1):42–49

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76:1–10

Joy J, Raj AK, Kunhamu TK, Jamaludheen V, Jayasree K (2019) Fodder production and carbon stock of calliandra under coconut plantation. Range Manag Agrofor 40(1):109–117

Jwel B, Mohapatra SC, Sasmita B (2019) Performance of fodder grasses with fast growing timber trees under silvipastoral system in rainfed coastal ecosystem. Environ Ecol 37(4B):1521–1524

Kamaliah N, Salim S, Abdullah S, Nobilly F, Mat S, Norhisham AR, Tohiran KA, Zulkifli R, Lechner AM, Azhar B (2022) Evaluating the experimental cultivation of edible mushroom, Volvariella volvacea underneath tree canopy in tropical agroforestry systems. Agroforest Syst 96:35–47. https://doi.org/10.1007/s10457-021-00685-9

Kamipang PPR (2015) Identifikasi Nilai Konservasi Tinggi. Kalimantan Tengah Indonesia

Karthika KS, Philip PS, Anilkumar KS (2019) Significance of soil carbon studies in plantation based ecosystems. Harit Dhara 2(2):19–21

Kaya M, Kammesheidt L, Weidelt HJ (2002) The forest garden system of Saparua island Central Maluku, Indonesia, and its role in maintaining tree species diversity. Agrofor Syst 54(3): 225–234

Kazi AA, Tandel MB, Pathak JG, Prajapati DH (2017) Potentiality of colocasia intercrop under naturally occurring palmyra palm (*Borassus flabellifer* L.). J Tree Sci 36(1):58–61

Kehlenbeck K, Maass BL (2004) Crop diversity and classification of homegardens in Central Sulawesi, Indonesia. Agrofor Syst 63(1):53–62

Khandekar RG, Nagwekar DD, Sawant VS, Gurav SS, Haldankar PM (2015) *Morinda citrifolia* as a suitable mixed crop in coconut under Konkan region of Maharashtra. J Indian Soc Coastal Agric Res 33(2):55–57

Khasanah NM, Perdana A, Rahmanullah A, Manurung G, Roshetko JM, van Noordwijk M (2015) Intercropping teak (Tectona grandis) and maize (Zea mays): bioeconomic trade-off analysis of agroforestry management practices in Gunungkidul, West Java

Kittur BH, Sudhakara K, Kumar BM, Kunhamu TK, Sureshkumar P (2016) Bamboo based agroforestry systems in Kerala, India: performance of turmeric (*Curcuma longa* L.) in the subcanopy of differentially spaced seven-year-old bamboo stand. Agrofor Syst 90(2):237–250

Köhler M, Hanf A, Barus H, Hendrayanto, Hölscher D (2014) Cacao trees under different shade tree shelter: effects on water use. Agroforest Syst 88:63–73. https://doi.org/10.1007/s10457-013-9656-3

Krishnakumar V (2004) Management of homegardens and their economic prospects under coastal agroecosystem. J Indian Soc Coastal Agric Res 22:137–141

Kumar BM (1994) Agroforestry principles and practices. In: Trees and tree farming. Peekay Tree Research Foundation, Cochin, pp 25–64

Kumar BM (2005) Land use in Kerala: changing scenerios and shifting paradigms. J Trop Agric 43(1–2):1–12

Kumar BM (2007) Agroforestry systems and practices of Kerala. Agroforestry systems and practices of India. New India Publishing Agency, New Delhi, pp 459–483

Kumar BM (2011) Species richness and and aboveground carbon stocks in the homegardens of central Kerala, India. Agric Eco Environ 140:430–440

Kumar BM, Kunhamu TK (2011) Quarter century of agroforestry research in Kerala: a compendium of research publications. Kerala Agriculture University, Kerala

Kumar KN, Maheswarappa HP (2019) Carbon sequestration potential of coconut-based cropping systems under integrated nutrient management practices. J Plant Crops 47(2):107–114

Kumar BM, Nair PKR (2004) The enigma of tropical homegardens. Agrofor Syst 61:135–152

Kumar BM, George SJ, Chinnamani S (1994) Diversity, structure and standing stock of wood in the homegardens of Kerala in peninsular India. Agrofor Syst 25:243–262. https://doi.org/10.1007/BF00707463

Kumar BM, Sajikumar V, Mathew T (1995) Floristic attributes of small cardamom (*Elettaria cardamomum* (L.) Maton) growing areas in the Western Ghats of peninsular India. Agrofor Syst 31:275–289

Kumar BM, George SJ, Jamaludheen V, Suresh TK (1998) Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. For Ecol Manag 112(1–2):145–163

Kumar BM, George SJ, Suresh TK (2001a) Fodder grass productivity and soil fertility changes under four grass+ tree associations in Kerala, India. Agrofor Syst 52(2):91–106

Kumar BM, Thomas J, Fisher RF (2001b) *Ailanthus triphysa* at different density and fertiliser levels in Kerala, India: tree growth, light transmittance and understorey ginger yield. Agrofor Syst 52(2):133–144

Kumar BM, Kumar SS, Fisher RF (2005) Galangal growth and productivity related to light transmission in single-strata, multistrata and 'no-over-canopy' systems. J New Seeds 7(2): 111–126

Kumar BM, Singh AK, Dhyani SK (2012) South Asian agroforestry: traditions, transformations, and prospects. In: Agroforestry—the future of global land use. Springer, Dordrecht, pp 359–389

Kumaravel P (2020) Management of animals in disaster, Doctoral dissertation, Tamil Nadu Veterinary and Animal Sciences University Madras. p 156

Kunhamu TK, Kumar BM, Viswanath S (2008) Does thinning affect litterfall, litter decomposition, and associated nutrient release in Acacia mangium stands of Kerala in peninsular India? Can J For Res 39(4):792–801

Kunhamu TK, Kumar BM, Samuel S (2011) Does tree management affect biomass and soil carbon stocks of Acacia mangium Willd. stands in Kerala, India? In: Kumar B, Nair P (eds) Carbon sequestration potential of agroforestry systems. Advances in agroforestry, vol 8. Springer, Dordrecht

Kunhamu TK, Niyas P, Anwar MF, Jamaludheen V, Raj AK (2015) Understorey productivity of selected medicinal herbs in major land management systems in humid tropical Kerala. Indian J Agrofor 17(2):1–8

Kunhamu TK, Aneesh S, Kumar BM, Jamaludheen V, Raj AK, Niyas P (2018) Biomass production, carbon sequestration and nutrient characteristics of 22-year-old support trees in black pepper (*Piper nigrum*. L) production systems in Kerala, India. Agrofor Syst 92(5):1171–1183

Leakey RRB, Sanchez PA (1997) How many people use agroforestry products? Agrofor Today 9(3):4–5

Leuschner C, Moser G, Hertel D, Erasmi S, Leitner D, CulmseeH SB, Schwendenmann L (2013) Conversion oftropical moist forest into cacao agroforest: consequencesfor carbon pools and annual C sequestration. Agrofor Syst 87:1173–1187

Liu W, Yao S, Wang J, Liu M (2019) Trends and features of agroforestry research based on bibliometric analysis. Sustainability 11(12):3473

Maclean RH, Litsinger JA, Moody K, Watson AK (1992) Increasing *Gliricidia sepium* and *Cassia spectabilis* biomass production. Agrofor Syst 20(3):199–212

Mahajan GR, Das B, Manivannan S, Manjunath BL, Verma RR, Desai S, Kulkarni RM, Latare AM, Sale R, Murgaonkar D, Patel KP (2021) Soil and water conservation measures improve soil carbon sequestration and soil quality under cashews. Int J Sediment Res 36(2):190–206

Maheswarappa HP, Sairam CV, Dhanapal R, Vidhan Singh T, Hegde MR (2000) Economic analysis of coconut based mixed farming systems. Cord XVI(1):37–46

Maheswarappa HP, Palaniswami C, Dhanapal R, Subramanian P (2010) Coconut based inter cropping and mixed cropping systems. In: Thomas GV, Krishanakumar V, Maheswarappa HP, Palaniswami C (eds) Coconut based cropping/farming systems. Central Plantation Crops Research Institute, Kasaragod, pp 9–31

Maheswarappa HP, Subramanian P, Kumari AG (2017) Influence of organic nutrient management practices for noni (*Morinda citrifolia*) when grown as an intercrop in coconut garden. ICAR

Martin FS, Van Noordwijk M (2009) Trade-offs analysis for possible timber-based agroforestry scenarios using native trees in the Philippines. Agrofor Syst 76(3):555–567

Martini E, Roshetko JM, van Noordwijk M, Rahmanulloh A, Mulyoutami E, Joshi L, Budidarsono S (2012) Sugar palm (*Arenga pinnata* (Wurmb) Merr.) for livelihoods and biodiversity conservation in the orangutan habitat of Batang Toru, North Sumatra, Indonesia: mixed prospects for domestication. Agrofor Syst 86(3):401–417

Mary F, Michon G (1987) When agroforests drive back natural forests: a socio-economic analysis of a rice-agroforest system in Sumatra. Agrofor Syst 5(1):27–55

Mathew T, Kumar BM, Suresh Babu KV, Umamaheswaran K (1992) Comparative performance of some multi-purpose trees and forage species in silvopastoral systems in the humid regions of southern India. Agrofor Syst 17:205–218

Mattsson E, Ostwald M, Nissanka SP, Pushpakumara DKNG (2015) Quantification of carbon stock and tree diversity of homegardens in a dry zone area of Moneragala district, Sri Lanka. Agrofor Syst 89(3):435–445

Mercado AR, Van Noordwijk M, Cadisch G (2011) Positive nitrogen balance of *Acacia mangium* woodlots as fallows in the Philippines based on ^{15}N natural abundance data of N_2 fixation. Agrofor Syst 81(3):221–233

Moench M (1991) Soil erosion under a successional agroforestry sequence: a case study from Idukki District, Kerala, India. Agrofor Syst 15:31–50

Mohanty S, Thakur NS, Gunaga RP, Gajbhiye N (2019) Influence of *Melia dubia* Cav. spatial geometries on growth, herbage yield and essential oil constituents of *Cymbopogon martinii* (Roxb.) Wats. J Essential Oil-Bearing Plants 22(3):630–648

Mohapatra KB, Chinara N (2014) Performance of straw mushroom (*Volvariella volvacea*) raised as an intercrop in coconut plantations of coastal Odisha. In: Proceedings of 8th international conference on mushroom biology and mushroom products (ICMBMP8), New Delhi, India, 19-22 November 2014. ICAR-Directorate of Mushroom Research, New Delhi, pp 314–317

Monalisa P, Panda NK, Mishra RSP (2020) Role of agroforestry in biomass production and soil moisture conservation in fruit based agri-silvi-horticultural systems with legume intercrops in Odisha. J Pharmacogn Phytochem 9(4):1307–1310

Muhamad D, Okubo S, Miyashita T, Takeuchi K (2013) Effects of habitat type, vegetation structure, and proximity to forests on bird species richness in a forest–agricultural landscape of West Java, Indonesia. Agrofor Syst 87(6):1247–1260

Mukhopadhyay R, Karisiddaiah SM (2014) The Indian coastline: processes and landforms. In: Landscapes and landforms of India. Springer, Dordrecht, pp 91–101

Mulukh DD, Mhaiske VM, Narkhede SS, Patil VK, Rane AD (2017) Adoption of agroforestry among smallholder farmers in Ratnagiri district of Maharashtra state. Indian J Trop Biodivers 25(2):165–171

Naik PK, Chakurkar EB, Manjunath BL, Swain BK, Singh NP (2011) Production potential of fodder maize as intercrop with cashew. Indian Veterinary Journal 88(8):130–132

Naik BS, Panda RK, Praveen J, Dass A, Madhu M (2013) Appraisal of the erosion status in the eastern coastal region of India. Indian J Soil Conserv 41(2):121–126

Nair PKR, Dagar JC (1991) An approach to developing methodologies for evaluating agroforestry systems in India. Agrofor Syst 16:55–81

Nair MA, Sreedharan C (1986) Agroforestry farming systems in the homesteads of Kerala, Southern India. Agrofor Syst 4:339–363

Nair GS, Sudhadevi PK, Kurian A (1991) Introduction of medicinal and aromatic plants as intercrops in coconut plantations. In: Raychaudhuri SP (ed) Recent advances in medicinal, aromatic and spice crops, vol 1. Today and Tomorrow's Printers & Publishers, New Delhi, pp 163–165

Nair PR, Kumar BM, Kumar SN (2018) Climate change, carbon sequestration, and coconut-based ecosystems. In: The coconut palm (Cocos nucifera L.)—research and development perspectives. Springer, Singapore, pp 779–799

Newaj R, Chaturvedi OP, Kumar D, Prasad R, Rizvi RH, Alam B, Handa AK, Chavan SB, Singh AK, Chaturvedi M, Karmakar PS (2017) Soil organic carbon stock in agroforestry systems in western and southern plateau and hill regions of India. Curr Sci 112(11):2191–2193

Newaj R, Kumar D, Rizvi R, Chaturvedi OP, Prasad R, Alam B, Chavan S (2018) Carbon sequestration potential of agroforestry systems existing on farmer's field in different states of the country, pp 406–428

Noble IR, Dirzo R (1997) Forests as human-dominated ecosystems. Science 277(5325):522–525

NRCAF (2014) Final report of 'Development of bamboo-based agroforestry systems for six agro-climatic zones. National Research Centre for Agroforestry, Jhansi, pp 1–24

Padma E, Ramanandam G, Rao AD, Kalpana M, Maheswarappa HP (2018) Performance of medicinal and aromatic crops as intercrops in coconut garden under east coast of Andhra Pradesh. Int J Pure App Biosci 6(2):421–426

Palei HS, Debata S, Sahu HK (2020) Diet of sloth bear in an agroforest landscape in eastern India. Agrofor Syst 94(1):269–279

Pandey CB, Singh RK (2010) Organic black pepper (*Piper nigrum*) cultivation on Gliricidia standards in coconut (*Cocos nucifera*) plantations in South Andaman: organic matter production and recycling of nutrients. Indian J Agric Sci 80(11):1–10

Pandey CB, Lalita S, Rai RB, Din M (2005) Traditional homestead farming systems and their variants in Andaman and Nicobar, India: an analysis of structure and economics. Indian J Agrofor 7(1):1–15

Pandey CB, Rai RB, Singh L (2007) Seasonal dynamics of mineral N pools and N-mineralization in soils under homegarden trees in South Andaman, India. Agrofor Syst 71(1):57–66

Pandey SBS, Pandey M, Jadeja DB, Tandel MB, Nayak D (2017) Growth and yield of ginger (*Zingiber officinale* L) under Sapota-Jatropha based agroforestry systems in south Gujarat. J Pharmacogn Phytochem 6(6):247–251

Parikesit TK, Tsunekawa A, Abdoellah OS (2005) *Kebon tatangkalan:* a disappearing agroforest in the Upper Citarum Watershed, West Java, Indonesia. Agrofor Syst 63:171–182. https://doi.org/10.1007/s10457-004-1182-x

Patil SJ, Mutanal SM, Patil HY, Shahapurmath G, Maheswarappa V (2010) Performance of Sapota-Teak based agroforestry system in hill zone of. Indian J Agrofor 12(1):27–34

Peyre A, Guidal A, Wiersum KF, Bongers FJJM (2006) Dynamics of homegarden structure and function in Kerala, India. Agrofor Syst 66(2):101–115

Philpott SM, Bichier P, Rice RA, Greenberg R (2008) Biodiversity conservation, yield, and alternative products in coffee agroecosystems in Sumatra, Indonesia. Biodivers Conserv 17(8):1805–1820

Raj AK, Kunhamu TK, Jamaludheen V, Kiroshima S (2016a) Forage yield and nutritive value of intensive silvopasture systems under cut and carry scheme in humid tropics of Kerala, India. Indian J Agrofor 18(1):47–52

Raj RM, Raj AK, Prakash A (2016b) Fodder yield and nutritive value of subabul (*Leucaena leucocephala* Lam.) under diverse management regimes in coconut garden. Indian J Agrofor 18(2):79–85

Rajasekharan P, Veeraputhran S (2002) Adoption of intercropping in rubber smallholdings in Kerala, India: a Tobit analysis. Agrofor Syst 56:1–11

Rakesh SS, Davamani V, Kamaludeen SP, Maragatham S, Lakshmanan A, Parameswari E, Velmurugan M (2020) Carbon sequestration potential of oil palm plantations in Tamil Nadu regimes, India. Int Res J Pure Appl Chem 21(11):7–17

Rane AD, Chandramouli S, Viswanath S (2016) Can *Dendrocalamus stocksii* (munro.) be the ideal multipurpose bamboo species for domestication in Peninsular India. J Bamboo Ratt 15(1-4): 23–32

Rane AD, Narkhede SS, Dalvi VV, Patil VK, Haldankar PM, Dodake SB, Dosani AAK, Bhattacharyya T (2018) Green Gold Manga Bamboo (*Dendrocalamus stocksii*) for commandable profit from cultivable wasteland. Adv Agric Res Technol J 2(2):141–152

Ravi R, Buvaneswaran C, Venkatesh A, Prasad R (2013) Growth and productivity of Casuarina equisetifolia in farmlands. Indian J Agrofor 15(1):36–44

Rawat P, Narkhede SS, Rane AD, Mhaiske VM, Dalvi VV (2017) Allelopathic effect of leaf leachates of solid bamboo *Dendrocalamus stocksii* (Munro.) on growth and yield of *Eleusine coracana* L (Gaertn.). Indian J Agrofor 19(2):79–82

Rocha D, Kunhamu TK, Santhoshkumar AV, Jamaludheen V (2017) Biomass and carbon stocks in 12-year-old Acacia mangium managed at variable density and pruning regimes in central Kerala, India. Indian J Agrofor 19(1):69–74

Rodriguez S, Sridhar A (2010) Harbouring Trouble: The Social and Environmental Upshot of Port Growth in India. Bangalore, Dakshin Foundation, p 62

Roe S, Streck C, Obersteiner M, Frank S, Griscom B, Drouet L, Fricko O, Gusti M, Harris N, Hasegawa T, Hausfather Z (2019) Contribution of the land sector to a 1.5 C world. Nat Climate Change 9:817–828

Roshetko JM, Bertomeu M (2015) Multi-species and multifunctional smallholder tree farming systems in Southeast Asia: timber, NTFPs, plus environmental benefits. Ann Silvic Res 39(2): 62–69

Roshetko JM, Delaney M, Hairiah K, Purnomosidhi P (2002) Carbon stocks in Indonesian homegarden systems: can smallholder systems be targeted for increased carbon storage? Am J Altern Agric 17(3):138–148

Routray SL, Bhol N, Nayak RK, Mohapatra SR (2018) Biomass production and carbon sequestration of mangium (*Acacia mangium* Willd.) under varying plant spacing. Indian For 144(6): 527–531

Roy Chowdhury S, Kumar A, Brahmanand PS, Ghosh S, Mohanty RK, Jena SK, Sahoo N, Panda GC (2011) Application of bio-drainage for reclamation of waterlogged situations in Deltaic Orissa. Research Bulletin 53. Directorate of Water Management, (ICAR), Bhubaneswar, p 32

Rubber Board (2011) Rubber grower's guide, pp 17–19

Ruslanjari D, Suryanto P, Alam T (2020) Optimization management for Chili *(Capsicum annum* L.) production in agroforestry system with coconut (*Cocos Nucifera* L.) on local protected coastline areas. Indones J Geogr 52(3):397–401

SAC (2012) Coastal zones of India. Published by Space Application Center (ISRO), Ahmedabad. https://vedas.sac.gov.in/vedas/downloads/atlas/Seashore/Vol-2-Full.pdf

Saha SK, Nair PR, Nair VD, Kumar BM (2009) Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. Agrofor Syst 76(1):53–65

Saha SK, Nair PKR, Nair VD, Kumar BM (2010) Carbon storage in relation to soil size-fractions under some tropical tree-based land-use systems. Plant Soil 328:433–446

Salma I, Masrom AM, Raziah ML (2006) Diversity and use of traditional fruit species in selected home gardens or fruit orchards in Malaysia. J Trop Agric Food Sci 34(1):149

Saravanan S, Buvaneswaran C, Veeramani T, Jayaraj RSC (2012) *Casuarina equisetifolia*—cotton based agroforestry system in Cauvery delta zone of Tamil Nadu for higher economic returns. In:

Jayaraj RSC, Warrier RR, Nicodemus A, Kumar NK (eds) Advances in casuarina research in India, proceedings of the 2nd national seminar on casuarinas. Institute of Forest Genetics and Tree Breeding, Coimbatore, pp 385–390

Schultz RC, Colletti JP, Isenhart TM, Marquez CO, Simp-kins WW, Ball CJ (2000) Riparian forest buffer practices. In: Garrett HE, Rietveld WJ, Fisher RF (eds) North American agroforestry: an integrated science and practice. American Society of Agronomy, Madison, WI, USA. University Press, Cambridge, pp 189–281

Shial G, Mohapatra TMA (2017) Study of *Acacia auriculiformis* based agroforestry practices in coastal district of Bhadrak, Odisha. J Pharmacogn Phytochem 6(6):361–364

Shinde VV, Maheswarappa HP, Ghavale SL, Sumitha S, Wankhede SM, Haldankar PM (2020) Productivity and carbon sequestration potential of coconut-based cropping system as influenced by integrated nutrient management practices. J Plant Crops 48(2):103–110

Siarudin M, Rahman SA, Artati Y, Indrajaya Y, Narulita S, Ardha MJ, Larjavaara M (2021) Carbon sequestration potential of agroforestry systems in degraded landscapes in west Java, Indonesia. Forests 12(6):714

Siju T, George KT, Radha L (2012) Changing dimensions of intercropping in the immature phase of natural rubber cultivation: a case study of pineapple intercropping in central Kerala. Nat Rubber Res 25(2):164–172

Singh NR, Arunachalam A, Dobriyal MJ, Bhusaraand JB, Gunaga RP (2017) Crop biomass and yield patterns of dominant agroforestry systems of Navsari district, Gujarat, India. Indian J Agrofor 19(2):72–78

Singh NR, Arunachalam A, Devi NP (2019) Soil organic carbon stocks in different agroforestry systems of south Gujarat. Range Manag Agrofor 40(1):89–93

Subbana S, Viswanath S (2018) Economic analysis of cultivation of bamboo (*Bambusa balcooa* Roxb. and *Dendrocalamus stocksii* Munro.) in Konkan belt of Maharashtra, India. J Bamboo Ratt 17(2):36–52

Subramanian P, Biddappa CC, Maheswarappa HP, Dhanapal R, Palaniswami C (2000) Feasibility studies of growing Glyricidia sepium as intercrop in coconut garden under littoral sandy soil. J Plant Crops 28(3):212–217

Sujatha S, Bhat R, Kannan C, Balasimha D (2011) Impact of intercropping of medicinal and aromatic plants with organic farming approach on resource use efficiency in arecanut (*Areca catechu* L.) plantation in India. Ind Crops Prod 33(1):78–83

Sundarapandian SM, Amritha S, Gowsalya L, Kayathri P, Thamizharasi M, Dar JA, Srinivas K, Gandhi S (2013) Estimation of biomass and carbon stock of woody plants in different land-uses. For Res 3(115):1–2

Sureshbhai PJ, Thakur NS, Jha SK, Kumar V (2017) Productivity and carbon sequestration under prevalent agroforestry systems in Navsari district, Gujarat, India. Int J Curr Microbiol Appl Sci 6(9):3405–3422

Tajuddin I (1986) Integration of animals in rubber plantations. Agrofor Syst 4(1):55–66

Thakur S, Kumar BM, Kunhamu TK (2015) Coarse root biomass, carbon, and nutrient stock dynamics of different stem and crown classes of silver oak (*Grevillea robusta* A. Cunn. ex. R. Br.) plantation in Central Kerala, India. Agrofor Syst 89(5):869–883

Thampan PK (1996) Coconut for prosperity. Gandhi Nagar, Peekay Tree Crops Development Foundation, p 271

Thangam M, Safeena SA, Devi SP, Singh NP (2014) Performance of heliconia-an exotic cut flower crop as intercrop in coconut under coastal climatic conditions of Goa. J Indian Soc Coast Agric Resh 32(2):37–41

Ulahannaan S, Mathew JJ, Sajeshkumar NK, Vazhacharickal PJ (2014) Pineapple (*Ananas comosus*) cultivation as an intercrop in rubber replant: effects on soil chemical and physical properties. Int J Adv Life Sci 7:574–579

UNEP (2006) Marine and coastal ecosystems and human well-being: a synthesis report based on the findings of the Millennium Ecosystem Assessment. UNEP, Nairobi, p 76

UNEP-WCMC (2006) In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs. UNEP-WCMC, Cambridge, p 33

UNICEF (2020) UNICEF data: cross-sector indicators. UNICEF, New York. https://data.unicef.org/resources/data_explorer/unicef_f/?ag=UNICEF&df=GLOBAL_DATAFLOW&ver=1.0&dq=IDN.NT_ANT_WHZ_NE3+NT_ANT_HAZ_NE2+NT_ANT_WHZ_NE2+NT_ANT_SAM_T..&startPeriod=2016&endPeriod=2020

Varsha KM, Raj AK, Kurien EK, Bastin B, Kunhamu TK, Pradeep KP (2019) High density silvopasture systems for quality forage production and carbon sequestration in humid tropics of Southern India. Agrofor Syst 93(1):185–198

Venkatesh A, Choudhuri NC, Kundu A, Medhi RP (2010) Introduction and evaluation of the performance of Japanese quail (*Coturnix coturnix japonica*)—a new component of homegardens in South Andaman. Indian J Agrofor 12(10:35–39

Visalakshi M, Jawaharlal M, Ganga M (2015) Intercropping in cashew orchards. Acta Hortic 1080: 295–298. https://doi.org/10.17660/ActaHortic.2015.1080.38

Vishwajith KP, Sahu PK, Dhekale BS, Noman MD, Mishra P (2015) Exploring the feasibility of arecanut based farming systems in augmenting farm economy-a case study in Karnataka, India. J Crop Weed 11:127–133

Viswanath S, Dhanya B, Rathore TS (2007) Domestication of *Dendrocalamus brandisii* in upland paddy fields in Cdorg, Karnataka. J Bamboo Ratt 6:215–221

Wardah, Toknok, Zulkhaidah B (2011) Carbon stock of agroforestry systems at adjacent buffer zone of Lore Lindu national park, Central Sulawesi. J Trop Soils 16(2):123–128

Weersum KF (1982) Tree gardening and taungya on Java: examples of agroforestry techniques in the humid tropics. Agrofor Syst 1(1):53–70

Weinstock JA (1994) Rhizophora mangrove agroforestry. Econ Bot 48(2):210–213

Wiryono W, Puteri VNU, Senoaji G (2016) The diversity of plant species, the types of plant uses and the estimate of carbon stock in agroforestry system in Harapan Makmur Village, Bengkulu, Indonesia. Biodivers J Biol Divers 17(1):249–255

World Bank (2019) Indonesia overview. World Bank, New York

WRI [World Resources Institute] (2020) Climate watch historical GHG emissions. World Resources Institute, Washington, DC. https://www.climatewatchdata.org/ghg-emissions

Yimyam N, Rerkasem K, Rerkasem B (2003) Fallow enrichment with pada (*Macaranga denticulata* (Bl.) Muell. Arg.) trees in rotational shifting cultivation in northern Thailand. Agrofor Syst 57(2):79–86

Zhang Y, Hou X (2020) Characteristics of coastline changes on southeast Asia Islands from 2000 to 2015. Remote Sens 12(3):519. https://doi.org/10.3390/rs12030519

Chapter 15
Biodiversity and Ecosystems Services of the Agroforestry Systems of the Himalayan Region: An Overview

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Abstract Natural ecosystems of the Himalayas such as forests, grassland, and agriculture provide innumerable services to humans. Due to the degradation of natural ecosystems and population pressure, the importance of age-old agroforestry practices has gained attention for their provision of diverse ecosystem services besides being a viable option for climate-smart agriculture. This chapter aims to provide a synthesis of the literature on the subject using a systematic review approach. The Himalayan agroforestry systems have been classified based on the nature of their components in six major categories and two subcategories. In terms of ecosystem services, studies on agroforestry systems have placed greater emphasis on the provisioning and regulating services as compared to the cultural and supporting services. The ecosystem services varied across the agroforestry types depending on the physiographic location and environmental conditions. The Eastern Himalayan agroforests reported a higher potential for carbon storage and sequestration than those of the Western Himalayas. The agroforestry system prevalent in the region supports the livelihood of millions of people by securing food and financial flow to communities. In addition, they play a key role in forest and biodiversity conservation, improving soil fertility and water conservation, and creating opportunities for recreational, cultural, and spiritual services. Substantial evidence also exists for the potential of agroforestry for the mitigation of climate change in the region through

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capturing carbon in plant biomass and soil. The evidence presented in this review suggests that agroforestry systems provide several provisioning and regulating services, and therefore, we recommend that it be promoted as a climate-smart agriculture to ensure human well-being and livelihood security in the region.

Keywords Biodiversity · Climate-smart agriculture · Climate action · Food security · Financial security · Safety net

15.1 Introduction

The Himalayan region, due to its vastness and variability in bioclimatic conditions and topography, hosts several types of ecosystems including forests, agricultural lands, agroforestry, rivers, glaciers, and many more that provide various services to the people. The ecosystem services coming from the Himalayan ecosystems are the source of livelihood to the people in the form of food, timber, fibre, medicine as well as water for drinking and irrigation (Kumar et al. 2002; Palacios Bucheli and Bokelmann 2017; Sharma and Chettri 2021) and play a key role in climate regulation, carbon storage, and the maintenance of cultural values (Sharma et al. 2015; Chaudhary et al. 2017; Xu et al. 2019). Due to their significant ecological contribution, the agricultural techniques or practices adopted in the mountains will have a significant impact on the other ecosystems beyond the mountains. Some workers have reported that the forests and agroforestry systems in the mountains help to stabilize headwaters, prevent flooding and landslide, and maintain steady year-round flows of water vital for the densely populated downstream areas (Molden et al. 2014; Mukherji et al. 2015). However, the quality and quantity of ecosystem services have been reported to decrease in most of the ecosystems due to anthropogenic activities, which have also influenced natural phenomena such as land sliding, precipitation, and climate (Xu et al. 2019; Sharma and Chettri 2021).

Services and resources provided by ecosystems are termed as ecosystem services and categorized under four different types by the Millennium Ecosystem Assessment (MEA) as provisioning services providing goods, regulating services that regulate ecosystems, cultural and supporting services that provide cultural, religious, recreational, educational, and other services to the mankind (Gupta et al. 2020). These services of the mountains agroforestry systems assist the mountain communities in a variety of ways by acting as a safety net during natural disaster-related crop failure and economic distress (Mavhura et al. 2013). Moreover, indigenous mountain communities rely on agroforestry for food, fodder, fuel, medicine, timber, and raw materials for handicrafts, and for collecting plants used for practicing religious rites and rituals (Palacios Bucheli and Bokelmann 2017).

In this chapter, we attempt to analyse biodiversity and ecosystem services of the Himalayan agroforestry systems for biodiversity conservation, carbon sequestration, and improvement of soil fertility.

15.2 Physical Setting and Biodiversity of the Indian Himalayan Region

The Indian Himalayan Region (IHR) is geographically located in between 23.23–34.08° N and 73.17–95.51°E covering an area of 530,000 km^2 in India. This area includes 11 states and 2 union territories from the eastern to the western Himalayan region. The Eastern Indian Himalayas covers eight different states: Assam, Arunachal Pradesh, Mizoram, Meghalaya, Manipur, Nagaland, Sikkim, and Tripura representing 26.3 million hectares (M ha) equivalent to 8% of the total geographical area of India (Roy et al. 2012). The Eastern Indian Himalayas is situated at the confluence of the Indo-Chinese, Indo-Malayan, and Indian biogeographical realms falling within one of the biodiversity hotspots of the world, the Indo-Burma biodiversity hotspot. The Western Indian Himalayas is also home to one-tenth of the world's known higher-altitude plant and animal species and half of India's native plant species (Padma 2014). The Western Himalayas are particularly rich in biodiversity, including the Indian states of Himachal Pradesh, Jammu and Kashmir, Uttarakhand, and Sikkim, where elevations vary from 300 m to more than 6000 m and where the mountains thus act as a natural barrier to species migration (Padma 2014). The Himalayas, which are geologically young mountains, consist of three main mountain ranges series running parallel to each other: the Siwalik Hills on the south, the altitude ranges from 900 to 1100 m; the middle Himalayas, which is the highest and central range, the altitude ranging between 3700 and 4500 m and the Tibetan Himalayas on the north, the average altitude is about 6000 m. In response to variations in climate, geology vegetation varies widely from tropical rainforests-like communities to alpine meadows and scrubs. Both the eastern and western Himalayas have mountain soil but the eastern Himalayan soil is dominated by acidic acrisol prone to erosion while that of the Western Himalayas is mainly alkaline calcareous soil but depending on the elevation and climate slight variations are reported (Table 15.1). In contrast, the north-eastern regions have slightly acidic red and laterite alluvial soil.

15.3 Main Agroforestry Systems

Among the agricultural systems of the mountainous region, agroforestry is an age-old practice developed through generational knowledge and experiences with socioecological processes to cope with environmental changes (Reid et al. 2005; Grêt-Regamey et al. 2012; Sayer et al. 2013). Agroforestry has gained momentum due to its role in climate action currently, yet it remained one of the important forms of agricultural practices of the mountains. In the Himalayan region of India, mountain agroforestry is mainly practiced in an area of 6.51 million ha comprising of the western Himalayas (Jammu and Kashmir including Ladakh, Himachal Pradesh, and Uttarakhand), Eastern Himalayas (Arunachal Pradesh, Sikkim, and hills of

Table 15.1 Agroforestry types, climatic, and altitudinal zone, from the Indian Himalayan region

Region/states	Climate and soil	Agroforestry types	References
Western Himalaya Jammu Kashmir and Ladakh, Himachal Pradesh, Uttarakhand Altitude (<1000 to >2500 m)	Subtropical to Alpine Alkaline to slightly acidic soil, calcareous to non-calcareous depending on the elevation	Agrisilvicultural Agrihorticultural Silvopastoral Agrihortisilvicultural Home gardens	Sehgal et al. (1990), Patiram (1994), Kashyap et al. (2014), Kumar et al. (2018), ISFR (2019)
Eastern Himalaya Arunachal Pradesh, Assam, Sikkim, Hills districts of West Bengal, Manipur, Meghalaya, Mizoram, Nagaland, Tripura Altitude (<1000 to >2500 m)	Tropical to Alpine Acidic, Acrisols weathered acid soils prone to erosion. Soil is classified under five orders—inceptisols, entisols, alfisols, ultisols, and mollisols	Shifting cultivation Agrisilvihorticultural Agrihorticultural Hortisilvicultural Agrihortipastoral Agrihortisilvopastoral Home gardens Livestock and sericulture based	Sehgal et al. (1990), Patiram (1994), Singh et al. (2014), Kumar et al. (2018), ISFR (2019), Sharma and Chettri (2021)

Darjeeling and Assam) and the north-eastern hilly states of Manipur, Mizoram, Nagaland, Meghalaya, Tripura, and Assam (Table 15.1). However, the Himalayan region comprises Nepal, Bhutan, and parts of Tibet and Pakistan too besides the Indian Himalayas.

The classification of the agroforestry systems has always remained a complex process due to the multiple criteria used for classification and putting them under a single classification is not possible (Nair 1985). Widely accepted and important criteria used for classification are structural classification—the nature and arrangement of components, functional-production and sustainability, the agro-ecological zone that varies across different regions, and socioeconomic conditions depending on the production, technology, and management input. Based on the nature of components in the agroforestry systems, (Nair 1985) classified the agroforestry systems as: (1) Agrisilvicultural: agriculture crops along with trees/vines species; (2) agrosilvipastoral: agriculture crops + animals/pasture and tree species; (3) silvopastoral-pasture/animals and trees; and (4) others including woodlots, apiculture with trees and aquasilviculture, etc.

Differences in geology, climatic, and soil factor between the Indian eastern and western Himalayas have given rise to region-specific agroforestry systems. A detailed description of the agroforestry types, soil, and climatic conditions prevailing in the Indian eastern and western Himalayan region is presented in Table 15.1. The Himalayan agroforestry systems unlike the other agroforestry practices in other regions are mostly subsistence in nature except for a few systems which are intermediate agroforestry systems with diverse components. Besides the trees, horticultural plantations such as apple (*Malus pumila*), peach (*Prunus persica*), apricot (*P. armeniaca*), plum (*P. domestica*), almond (*P. amygdalus*), mandarin (Citrus reticulata), etc. are used as a tree component in many of these systems (Kashyap et al. 2014). Furthermore, most of the agroforestry systems of the region support livestock for sustenance during some disasters, climate irregularities, and

Fig. 15.1 Large cardamom-based agroforestry system of Eastern Himalaya (hortisilvicultural)

extreme weather events which are frequent in the region. Hence, the horticultural crops form one of the important components for the classification of the Himalayan agroforestry systems (Figs. 15.1 and 15.2). Additionally, silvopastoral systems are scarce in the Himalayas and limited to high-altitude regions only, but agrihortisilvipastoral systems/home gardens that supply fodder along with crops are common (Fig. 15.3). Moreover, due to variation in landscape, climate, and other environmental conditions of the Himalayan region, agroforestry systems vary widely in this region. For more details, see Kashyap et al. (2014) for the North-Western Himalayan region and Singh et al. (2014) for the North-eastern Himalayas, who have given an extensive account of agroforestry systems, their role in soil conservation, ecosystem stability, and livelihood security. However, all these systems support livestock in one form or the other to meet the domestic requirements of the people as every household of the Himalayan region maintains five to eight livestock units traditionally (Banyal et al. 2016).

15.3.1 Biodiversity Conservation

15.3.1.1 Conservation of Tree Diversity

Mountains ecosystems are centres of biological diversity (Sharma et al. 2008) due to their diverse gene pools, and species diversity (Myers et al. 2000). However, certain

Fig. 15.2 Mandarin-based agroforestry system of the Himalayan region (agrihorticultural)

Fig. 15.3 Himalayan home gardens agroforestry systems

factors threaten the rich biodiversity of these ecosystems, including hunting, timber extraction, intensive grazing, conversion of forest to other land uses, and climate change (Sharma et al. 2008). Adopting agroforestry systems instead of conventional farming practices such as terraced cropping and slash and burn agriculture in these areas may help to reduce the pressure on these systems. The high-altitude Indian agroforestry systems use various tree species which directly or indirectly help in the biodiversity conservation of the area. Major tree species used in the eastern Himalayan systems include different tree species such as *Acacia* spp., *Albizia* spp., and *Alnus nepalensis* that help in nitrogen-fixation; and *Ficus hookeri* and *Eucalyptus* having multipurpose uses. Additionally, other economically important trees such as species of *Parkia, Juglans*, different species of *Prunus,* and *Pinus* that yield edible fruits along with *Schima wallichii* are often grown for timber (Table 15.2). Besides these, other tree species common in the western Himalayan agroforestry systems include species of *Populus*, S*alix,* and *Cedrus deodara,* at the higher altitude for timber and fuelwood (Kumar et al. 2009) while in the lower elevation fodder tree species such as *Grewia, Grevillea* and *Gmelina* along with fruit trees such as varieties of *Malus, Prunus, Pyrus* and *Morus* species are commonly grown. *Hippophae salicifolia* is another important tree species grown in the higher altitude region of the Himalayas for its fruit that can generate high income for the farmers due to its nutraceutical property and can also be used as fodder and fuelwood in this area. Tree diversity varies across the agroforestry practices of the Himalayan region (Table 15.2).

The use of multiple tree species in various systems is prominent which includes fodder, fruit, and other economically important trees species distributed in the agrihorti and silvopastoral agroforestry systems. The use of multi-purpose trees with fruit trees along crops has higher diversity in the system while the use of only fruits trees in the agrihorticultural system results in low plant diversity. Due to the conservation of diverse trees, agroforestry systems have been used as a tool for the conservation of biodiversity as they restrict the conversion of forest to grassland or cropland and therefore have 50–80% plant species similar to natural forests (Noble and Dirzo 1997). Additionally, the presence of multipurpose and underutilized trees in the agroforestry systems such as species of *Machilus* and *Acacia* help in releasing the pressure for fuelwoods and fodder by the locals in the natural forest (Huang et al. 2002) thereby, contributing to biodiversity conservation in the reserve forest. Besides trees, other herbaceous plants having medicinal and religious values such as *Ocimum sanctum, Ficus religiosa*, Ashoka trees, and varieties of heirloom species of crops are conserved in the agroforestry by the farmers.

15.3.1.2 Crop and Livestock Diversity

About 39% of the mountain people are more vulnerable to food insecurity and malnutrition (FAO 2015) due to poverty, inappropriate feeding practices, harsh climatic conditions, and loss of soil fertility due to soil erosion as a result of tough terrain and water scarcity leading to low yield of food crops (Kherallah et al. 2002). Agroforestry has been identified as one of the resilient farming practices of the mountains to ensure food security due to its capability to withstand the stress and shock of environmental and climate changes (Pandey et al. 2017). Besides the staple crops, vegetables, and fruits, the underutilized food crops such as maize, various millets, sea-buck-thorn (*Hippophae rhamnoides*), etc. incorporated in agroforestry

Table 15.2 Plant diversity of multipurpose trees, fruit trees, crop plants, pulses, and vegetables in different agroforestry systems

	Tree components		Crop components		
Agroforestry type	Multipurpose trees	Fruit trees	Staple	Pulses	Vegetables and spices
Agrisilvicultural	*Acacia* spp., *Eucalyptus* spp., *Euphorbia tirucalli, Ficus spp., G. robusta, Balanites aegyptiaca, Melia azedarach, Faidherbia albida, Grewia oppositifolia, Toona african, Celtis australis, Alnus nepalensis, Pinus wallichiana, Populus, Salix, Cedrus, and Junipers, Grewia optiva, Populus sp, Dalbergia sissoo, Senegalia catechu, Morus sp.–* (21species)	*Ziziphus spina-christi, Olea Africana, Carya illinoinensis*	Wheat, Maize, Great millet, Finger millet, Hay grass, Barnyard millet	Beans,	sugarcane, Garlic, Tomato potato, pumpkin, Chilly, Turmeric, Amaranth, Tapioca
Agrosilvopastoral	Eucalyptus spp., Ficus spp., *Michelia oblonga, Alnus nepalensis, Pinus kesiya, saligna, Grevellia robusta, Faidherbia albida, and Azadirachta indica (10)*	*Parkia roxburghi*	Maize, and Rice	Beans	–
Silvopastoral	*Pinus roxburghii, Celtis australis, Acacia catechu, Quercus leucotrichophora, Pyrus pashia, Pinus gerardiana, Cedrus deodara, Eucalyptus sp, Toona ciliata, Grewia optiva, Dalbergia sissoo,Senegalia catechu, Morus sp.* (12)	*Grasses*	–	–	–

Agrihorticulture	–	Mandarin, Walnut, Apple, Plum, Apricot, Malus spp., Pyrus spp., and Prunus spp., Coffee, Mango	Maize, Wheat, Barley, Millets, Oats	Soybean, Rajma,	Chilly, Garlic Radish, Peas, Cabbage, Cauliflower, Spinach, Mustard Potato, Brinjal, Wild carrot
Agrihortisilviculture	*Ficus spp., Eucalyptus spp., Albizia zygia, Canarium schweinfurthii, Ceiba pentandra, Celtis tessmannii, Gambeya lacourtiana, Milicia excels, Leucaena leucocephala, Mimosa tenuiflora, Albizia schimerana, Grewia oppositifolia, Toona ciliata, Celtis australis, Grewia optiva, Quercus leucotrichophora, Acacia catechu, Dalbergia sissoo, Ailanthus altissima, Salix tetraperma, Populus ciliata, Cedrus deodara and Abies pindrow*, *Armeniaca vulgar*, *Prunus salicina*, *Ziziphus jujuba, Hibiscus rosachinenesis*– (27)	Apple, Avocado, Palms, Mango, Walnut, Guava, Plum, Jackfruit, Citrus sp., Arecanut, Jamun, and Cashew nut, Coffee	Maize, Barnyard millet Buckwheat	Pea, Black Gram, Cowpea Soybean	Beans, Cucumbers, Squash, Maize, Tomato, Pepper Turmeric, Ginger and Pea
Hortisilviculture	*Albizia spp., Ficus spp., Dendrocalamus sp, Dalbergia sissoo, Derris robusta, Senna siamea, Alnus nepalensis, Schima wallichii, Machilus edulis, Lyonia ovalifolia, Macaranga pustulata, Litsea cubeba (12)*	*Persea American, Juglans regia,*	Tea, Coffee, and Cardamom	–	–

Table 15.3 Livelihood support from agroforestry in the Himalayan region (US$ per household per year)

Location	Components					Total USD	Source
	Farm crops	Livestock + livestock products	NTFP + MAP	Cash crops	Misc fodder + fuelwood		
Rasuwa, Nepal	_	325.84	_	_	_	325.84	Pandit (2008)
Upper belt Rasuwa, Nepal	19.23	82.55	83.33	16.59	47.31	249.01	Pandit et al. (2013)
Lower belt Rasuwa, Nepal	79.87	135.90	46.22	14.10	44.87	320.96	Pandit et al. (2013)
Farm based, Sikkim, India	2.81	275.34	9.71	469.23	6.60	763.69	Sharma and Sharma (2017)
Forest based, Sikkim, India	52.38	206.41	189.26	_	278.39	726.44	Sharma and Sharma (2017)
Alnus-cardamom, Sikkim, India	127.60	155.80	4.28	_	426.08	713.76	Sharma and Sharma (2017)
Forest cardamom, Sikkim, India	11.23	1216.79	25.39	11.60	188.09	1453.1	Sharma and Sharma (2017)
Albizzia-mandarin, Sikkim, India	22.22	955.84	20.66	2.85	178.77	1180.34	Sharma and Sharma (2017)
Hee-Martam, West Sikkim, India	22.79	2037.04	13.67	_	789.03	2862.53	Sharma and Sharma (2017)
Salar Tibetan Plateau, China	–	–	–	–	–	150	Zhu et al. (2021)
Western Himalayas *Grewia* based AFS	3.5	–	–	0.2	2.51	639.20	Arunachalam et al. (2019)
Western Himalayas Willow based AFS	17.26	–	–	–	315.27	3051.04	Arunachalam et al. (2019)
Cold desert Sea buckthorn based AFS	–	–	–	11	0.32	6391.14	Arunachalam et al. (2019)

constitute an important alternative crop for the people of this region during crop failure and famine (Table 15.3) thereby, providing food security. Furthermore, incorporating livestock such as cattle, poultry, and piggery as a component of agroforestry helps the mountain dwellers sustain a diversified diet even under unfavourable environmental conditions and hunger through any unforeseen conditions. Besides, domestication of wild and underutilized food provisioning plants, the introduction of exotic species, ensures the availability of diverse food plants (Torquebiau 1985) and advances food security and nutrient balanced diets (Susila et al. 2012) to the undernourished people of the region.

The incorporation of fruit trees and vegetables along with multipurpose trees, including fodder plants, is another aspect of the mountain agroforestry that helps sustain the mountains' harsh climatic conditions. A study on various agroforestry systems suggests that the agrisilvicultural form of agroforestry proves to be the best for providing food security (Huang et al. 2002) but in the Himalayas, the agrihortisilvicultural system of agroforestry seems to be the most favoured due to its diverse tree and crops components for provision of food security while silvopastoral systems the least productive. The agrisilvicultural, agrihorticultural, and agrihortisilvicultural systems that are more prevalent in the subtropical and temperate regions have more diverse food crops compared to silvopastoral and hortisilvicultural systems of the alpine regions. This is probably due to the inability of the crops to sustain the harsh alpine climatic conditions.

15.4 Ecosystem Services of Agroforestry Systems

The ecosystem services that benefit society are air quality, climate regulation carbon sequestration, water purification, pollination, and prevention of erosion and have been valued in the range of 16–54 trillion US dollars per year (Costanza et al. 1997). The Millennium Ecosystem Assessment (MA 2005) defined four categories of ecosystem services (Fig. 15.4), i.e., provisioning services, regulating services, cultural services, and supporting services that contribute to human well-being. The ecosystem services approach can save many ecosystems with high biodiversity and the willingness of society to protect their biodiversity. The Economics of Ecosystems and Biodiversity (TEEB) is a major global programme to draw attention to the tangible benefits of biodiversity and highlights the growing costs of biodiversity loss and ecosystem degradation (TEEB 2010). Important services provided by agroforestry systems in the Indian Himalayan region are discussed as follows:

15.4.1 Provisioning Services

The MA provisioning services describe the processes that yield foods, fibres, fuels, water, biochemicals, medicinal plants, pharmaceuticals, and genetic resources. The Economics of Ecosystems and Biodiversity (TEEB 2010) drew attention to the global economic benefits of biodiversity and highlighted the growing costs of biodiversity loss and ecosystem degradation. Biodiversity regulates all ecosystem services, but it can also be a service in itself (e.g. the existence value of a species

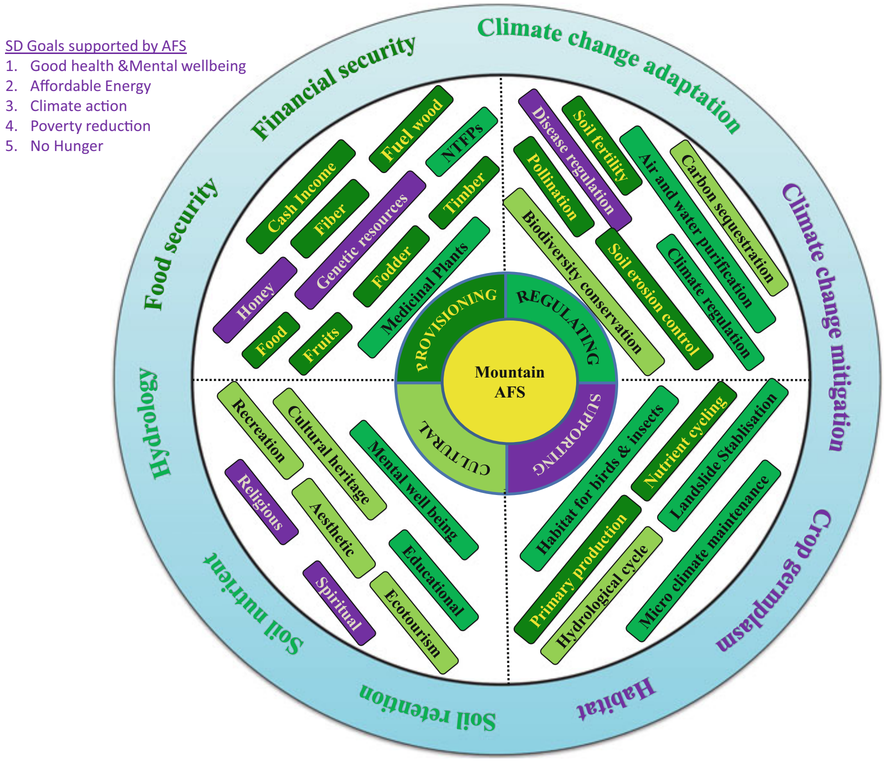

Fig. 15.4 Major ecosystem services and support from the agroforestry to the Himalayan communities

under cultural services) (Mace et al. 2012). Biodiversity is also considered to have an insurance value by providing resilience in the face of current or future changes in ecosystems and the services they provide. Some provisioning services of the agroforestry system are briefly described as follows:

15.4.1.1 Medicinal and Aromatic Plants

Medicinal and aromatic plants are another source of livelihood for the mountain people (Hoermann et al. 2010; Shah et al. 2018) and the agroforestry systems of the Himalayas host various medicinal and aromatic plants. The use of medicinal plants for traditional medicines has been officially endorsed by some of the developing countries such as China, Sri Lanka, India, Cuba, and Thailand, and about 80% of the population rely on this system (de Silva 1997; Rao et al. 2004). The traditional Himalayan agroforestry systems host and conserve many of the medicinal plants. For example, plants such as Tulsi (*Ocimum sanctum*), drumstick (*Moringa oleifera),* curry leaf (*Murraya koenigii*), and *Terminalia arjuna* are often used for their medicinal properties. An increase in the household income through farming of *Ocimum sanctum* in the agroforestry systems has been reported in the Western Himalayan state of Uttarakhand (Shah et al. 2019). Other aromatic plants often planted in the Western Himalayan agroforestry systems include *Withania somnifera, Andrographis paniculata, Mentha* sp., *Aconitum sp*, *Rauvolfia sp, Matricharia chamomilla,* and *Ocimum basilicum*. Interestingly, when cultivated these crops with peach (*Prunus persica*), the yield of peach fruit increased as compared to when grown without crops (Kashyap et al. 2014), Cultivation of turmeric (*Curcuma domestica*), and Zinger (*Zingiber officinale*) with *Populus deltoides* in Western Himalayan region is quite popular. Further, ginger, turmeric, large cardamom (*Amomum subulatum*), and black pepper (*Piper nigrum*) are widely cultivated with alder (*Alnus nepalensis*) and other trees in the north-eastern region (Singh et al. 2014).

15.4.1.2 Biomass Energy and Fuelwood

Biomass energy or fuelwood remained one of the major sources of energy used by people of the Himalayan mountains for ages (Bhatt and Sachan 2004a; Rawat et al. 2009) as 90% of the energy is derived from the burning of the fuelwood (Sharma et al. 1999, 2009). Lack of an alternative source of energy and extremely cold climate in the high altitude region enhanced fuelwood demand for cooking, heating (room and water), lighting, and livestock rearing leading to pressure on forest and ultimately deforestation (Osei 1993; Shanavas and Mohan Kumar 2003; Kumar and Sharma 2009). The demand for fuelwood varies with the season and climate of a region and increases with elevation (Bhatt et al. 1994, 2016; Singh et al. 2010) due to a decline in temperature. Also, it has been reported that households with livestock such as pigs and cattle require more firewood for cooking the kitchen and agricultural waste than households without livestock (Bhatt et al. 2016). Furthermore, the North-western Himalayan region reported higher fuelwood consumption than Eastern and Central Himalayan regions, mainly due to the unavailability of alternative energy sources and better and efficient means of burning the fuels (Maikhuri 1991). However, a recent study reported higher fuelwood consumption in the Eastern Himalayan region than that of the Western Himalayas which may be because of increased fuelwood availability in the Eastern Himalayas due to a reduction in shifting and Jhum cultivation and an increase in agroforestry systems in this region (Bhatt et al. 2016).

The pressure of high fuelwood demand on forests can be minimized and compensated by the different multipurpose tree species (MPT's) used in the Himalayan agroforestry systems particularly agrisilviculture and agrihortisilvopastoral systems, and residues of crops and dung of the cattle incorporated in agroforestry in extreme events (Kumar and Sharma 2009). Also, it has been reported that demand for fuelwood and shifting cultivation practice in the Eastern Himalaya especially north-east India leads to severe land degradation but agroforestry and Joint forest management programs can restore these areas (Bhatt et al. 2016) as it can provide fuelwood for the rural people thereby reducing pressures from the forests. Additionally, agroforestry practice can also save labour energy spent on fuelwood collections by various tribes of the Himalayan region, for example, 97.93 MJ capita^{-1} year^{-1} by the Jaintia tribe and 85.60 MJ capita^{-1} year^{-1} by the Khasi tribe (Bhatt and Sachan 2004b) 243.5 MJ capita^{-1} per year^{-1} by the Kacharis tribe and 92.5 MJ capita^{-1} per year^{-1} by the Nishi tribes of Northeast India (Maikhuri 1991).

15.4.1.3 Financial Benefits to the Local Community

Less farmable land to people ratio of the Himalayan region, for example, 66% of the Nepalese population practice farming in 23% of the land surface only (Pandit and Thapa 2004; Upadhyay et al. 2005), forced the mountain people to opt for subsistence agroforestry beyond the farming lands (Pandit et al. 2013) for sustenance and financial security. Few studies have highlighted the financial flow of the Himalayan agroforestry systems (Pandit et al. 2013; Sharma and Sharma 2017). Due to the similarities of crops, tree components including cash crops, and livestock in the different agroforestry systems of this region, the financial flow arising out of the products was not segregated according to the agroforestry types in this review. Financial benefits arising out of the different components of the Himalayan agroforestry are presented in (Table 15.3) which highlights the importance of agroforestry systems for the financial security of the people of this region. A study from Nepal concluded that the sale of agroforestry products including livestock and its products, fodder, fuelwood, fruits, and vegetables enhanced the income by three times as compared to those who did not practice agroforestry (Pandit et al. 2013) thereby providing regular financial flow for livelihoods. In Sikkim, a mountainous state of India, the average income generated through large cardamom only from agroforestry was USD 911 year^{-1} per household^{-1} (Sharma and Sharma 2017), while a study on Rasuwa district of Nepal revealed that average income fetched from livestock and its products was USD 325.84 year^{-1} per household^{-1} (Pandit 2008).

15.4.2 Regulating Services

The agroforestry systems sequester carbon from the atmosphere and influence the patterns of climate. Climate regulation refers to the influence that ecosystems have on the global climate by emitting greenhouse gases into the atmosphere or extracting carbon from the atmosphere. According to Gupta et al. (2020), agroforestry systems improve soil properties and processes, which play an important role in climate regulation through carbon sequestration and reducing greenhouse gas emissions, and provision of water through regulation of soil properties.

15.4.2.1 Soil Fertility Enhancement

Soils of the mountains are prone to erosion, a phenomenon responsible for the degradation of soil fertility due to the steep landscapes of the mountains. The litter layer on soil due to the litter inputs from trees and shrubs of the agroforestry systems and dense herbaceous vegetation such as forest-based and cardamom agroforestry can prevent soil erosion in the mountainous region of Eastern Himalaya (Sharma et al. 2016). Further, the use of nitrogen-fixing tree species such as *Albizia, Alnus* in many of the agroforestry systems of this region enhanced soil fertility through biological N fixation, for example, 9.52–95.25 kg N ha^{-1} $year^{-1}$ fixed by different agroforestry systems of Sikkim (Sharma et al. 2016) and Nagaland, 48.30–184.80 kg N ha^{-1} $year^{-1}$ (Kehie and Khamu 2018) (Table 15.4). Besides nitrogen fixation, these tree species also enhance the amount and solubilization of soil phosphorus for uptake by the plants (Sharma et al. 2007). Additionally, agroforestry because of its different components, trees/shrubs, crops, livestock, and fodder plants not only helps in sustaining the harsh environmental condition of the mountains but also enriches the soil through the addition of animal waste. Among the different Himalayan agroforestry systems, such as agrihortisilvicultural systems of the alpine/cold desert systems of Ladakh (Kumar et al. 2009) stores low soil nutrients due to the low organic matter in the soil as a result of less vegetation and depletion of nutrients by the cultivation of multiple crops on a rotation basis throughout the year (Table 15.4). In contrast, most of the agroforestry systems such as large cardamom-based and *Alder*-based systems adopted in the mountains are mainly forest-based with a single or few crops, including no-tillage soil management practice that conserves moisture and nutrients in the soil. However, the soil nutrient status of an ecosystem is a function of various factors such as edaphic conditions, topography, elevation, species composition, geological factors, microbial activity, etc. (Furtak and Gałązka 2019).

15.4.2.2 Carbon Storage and Sequestration

The agroforestry systems have the potential to mitigate global warming and climate change has been reported to be about 26 million metric tons of carbon, which will increase to 45 million metric tons by 2040 as they incorporate fast-growing woody species (IPCC 2001). Further, this form of agriculture has been adopted as a better alternative to the conventional farming system in the high altitude region as well as the low-lying areas to reduce deforestation, CO_2 emission to mitigate climate change and global warming (Mbow et al. 2014a).

Encouragement of agroforestry practices in the sensitive mountain ecosystems prone to deforestation and land use transformation can help minimize the ill effects of global warming and climate change and sustain the people. Himalayan agroforestry systems can capture and store carbon both in vegetation (ranging from 0.02 to

Table 15.4 Total nitrogen stock and nitrogen fixation and nitrogen fixation as a measure of soil fertility in the different Himalayan agroforestry systems

Agroforestry type	Components	Location	Total N kg ha^{-1}	Nitrogen fixation kg ha^{-1} $year^{-1}$	References
Agrisilviculture	Alnus+ vegetables	Nagaland, Eastern Himalaya	–	117	Kehie and Khamu (2018)
	Pecan nut+ crops	Almora, Western Himalayas	231	–	Yadav et al. (2017)
	Trees + crops	Himachal Pradesh, Western Himalayas	394		Singh et al. (2015)
Agrosilvopastoral	Multipurpose tree + crops	Meghalaya, Eastern Himalaya	496–584	–	Ramesh et al. (2015)
	Multipurpose fodder and timber trees+ bamboo	Sikkim, Eastern Himalaya	4360	59	Sharma et al. (2016)
Silvopastoral	Trees + grasses	Himachal Pradesh, India	405		Singh et al. (2015)
Agrihorticultural	Mandarin + vegetables	Sikkim, Eastern Himalaya	239	–	Sharma and Rai (2007)
	Coffee + vegetables	Bhaktapur, Eastern Himalaya Nepal	2786		Gautam et al. (2017)
	Mandarin & mango + crops	Himachal Pradesh, Western Himalayas	344		Singh et al. (2015)
Agrihortisilvicultural	Homestead	Assam, Eastern Himalayas	7455	–	Deb et al. (2008)
	Trees + fruits + crops	Ladakh, Western Himalayas	1		Kumar et al. (2009)
	Trees + fruits + crops	Himachal Pradesh, Western Himalayas	355		Singh et al. (2015)
Hortisilvicultural	Tea + MPTs	Assam, Eastern Himalayas	8400	–	Kalita and Nath (2016)

(continued)

Table 15.4 (continued)

Agroforestry type	Components	Location	Total N kg ha^{-1}	Nitrogen fixation kg ha^{-1} $year^{-1}$	References
	Forest+ cardamom	Sikkim, Eastern Himalayas	394	–	Lepcha and Devi (2020)
	Alnus+ cardamom	Sikkim, Eastern Himalayas	7650	95	Sharma et al. (2016)
	Forest + cardamom	Sikkim, Eastern Himalayas	5440	9.5	Sharma et al. (2016)
	Albizia- + mixed trees + mandarin	Sikkim, Eastern Himalayas	4400	20	Sharma et al. (2016)

54 Mg C ha^{-1}) as well as in soil across the different agroforestry types of the Eastern and Western Himalayas (Tables 15.5 and 15.6).

Removal of most parts of the biomass for human consumption in the agriculture-based agroforestry systems leads to a low amount of vegetation carbon in contrast to the horticultural agroforestry, due to the limitation of the extraction of plant parts. Moreover, the density and diversity of trees in the agroforestry system is the deciding factor that determines the amount of vegetation carbon storage and sequestration (Lepcha and Devi 2020). Fertilization by the addition of manure and compost including mulch accounts for the high amount of soil carbon in the agrihorticulture systems. A study on the subtropical agroforestry system of the Eastern Indian Himalaya reported higher vegetation biomass and carbon than that of its Western Himalayan counterpart (Lepcha and Devi 2019). However, many studies also concluded variations of carbon stock both in vegetation and soil due to a difference in elevation, agroforestry components, and management practices adopted (Rajput et al. 2017; Chisanga et al. 2018; Vikrant et al. 2020). Besides these, the growth habit and age of plants, and interaction of trees and crops also influence the biomass accumulation and carbon stock in the agroforestry systems (Jana et al. 2009; Kanime et al. 2013) thereby helping in locking a higher amount of the carbon and enhanced CO_2 mitigation (Vikrant et al. 2018).

The soil-plant ratio of ecosystems is another deciding factor for carbon accumulation and emission from an ecosystem, soils with a high soil-plant ratio are vulnerable to more CO_2 emission while with an increase in vegetation soil organic carbon storage increases (Rajput et al. 2017). A study claimed that a traditional cardamom agroforestry system of Sikkim Himalaya emits less CO_2 from the soil as compared to other ecosystems such as grassland, bamboo, and forest of North East India (Lepcha and Devi 2020) supporting the substantial role of agroforestry in mitigating global warming and climate. However, variation in climate, soil, and vegetation types in the Eastern and the Western Himalayan region could be another important factor that attributes to the carbon accumulation and emission pattern of

Table 15.5 Carbon stock, sequestration, and carbon emission from different agroforestry systems of the Eastern Himalayas

Agroforestry type	Location	Vegetation carbon stock (Mg C ha^{-1})	Annual vegetation carbon sequestration (Mg C ha^{-1})	C Emission (Mg CO_2 ha^{-1})	Reference
Agrosilvopastoral	Meghalaya, NE India	–	–		Ramesh et al. (2015)
	Sikkim, India	8.43	–		Sharma et al. (2016)
	Rasuwa, Nepal	48.6	0.97		Pandit (2008)
Agrihorticulture	Sikkim, India	5.47	–		Sharma and Rai (2007)
Hortisilviculture	Assam, NE India	54.67	–		Kalita and Nath (2016)
	Sikkim, India	38.47	5.49	12.71	Lepcha and Devi (2020)
	Sikkim, India	12.61	–		Sharma et al. (2016)
	Sikkim, India	5.13	–		Sharma et al. (2016)
	Sikkim, India	3.51	–		Sharma et al. (2016)

the Himalayan region. A growing body of evidence suggests that C emissions from soil can be reduced to 50% by 2050 of those in 2010 with suitable mitigation practices (Xu et al. 2020). Agroforestry practices seem to be one of the best available options, given the high SOC sequestration rates reported in several reviews and meta-analyses (Nath et al. 2021). A study from the Western Himalayan region concluded that agroforestry practices can minimize the vulnerability to climate change on farmers (Pandey et al. 2017) due to its self-regulating, adaptive capacity, diversified crops, and integration of livestock (Silici 2014) making this agricultural practice a sustainable land-use system for the mountains.

Table 15.6 Total vegetation carbon stock, sequestration, and carbon emission from different agroforestry systems of the Western Himalayas

Agroforestry type	Location	Vegetation carbon stock (Mg C ha^{-1})	Annual C sequestration (Mg C ha^{-1})	C Emission (Mg CO_2 ha^{-1})	Source
Agrisilvicultural	Himachal Pradesh, Western Himalayas	3.81	–	6.84	Goswami et al. (2013)
	Almora, Western Himalayas	21.93	1.67	–	Yadav et al. (2017)
	Uttarakhand, Western Himalayas	0.08–0.16	–	–	Vikrant et al. (2018)
	Uttarakhand, Western Himalayas	1.09	–	–	Vikrant et al. (2020)
	Himachal Pradesh, Western Himalayas	38.02	–	–	Singh et al. (2018)
Agrosilvopastoral	Ladakh, Western Himalayas	–	–	–	Kumar et al. (2009)
Silvopastoral	Himachal Pradesh, Western Himalayas	32.88	–	–	Chisanga et al. (2018)
Agrihorticulture	Himachal Pradesh, Western Himalayas	3.01	–	9.14	Goswami et al. (2013)
	Himachal Pradesh, Western Himalayas	14.59	–	–	Chisanga et al. (2018)
	Himachal Pradesh, Western Himalayas	30.29	–	–	Singh et al. (2018)
	Uttarakhand, Western Himalayas	0.02	–	–	Vikrant et al. (2018)
	Jammu & Kashmir, Western Himalayas	11.44	–	–	Zahoor et al. (2021)
	Himachal Himalayas, Western Himalayas	49.05	2.08	–	Rajput et al. (2017)
	Himachal Pradesh, Western Himalayas	36.35	–	–	Singh et al. (2014)

(continued)

Table 15.6 (continued)

Agroforestry type	Location	Vegetation carbon stock (Mg C ha^{-1})	Annual C sequestration (Mg C ha^{-1})	C Emission (Mg CO_2 ha^{-1})	Source
Agrihortisilviculture	Uttarakhand, Western Himalayas	0.01–0.06	–	–	Vikrant et al. (2018)
	Himachal Pradesh, Western Himalayas	42.43		–	Singh et al. (2018)
	Himachal Pradesh, Western Himalayas	38.37	–	–	Chisanga et al. (2018)
	Himachal Pradesh, Western Himalayas	6.09	–	8.52	Goswami et al. (2014)
Hortisilviculture	Himachal Pradesh, Western Himalayas	95.25	–	–	Rajput et al. (2017)

Table 15.7 Cultural and supporting ecosystem services of the Himalayan agroforestry systems

Sl. No	Cultural services	Supporting services	Reference
1.	Sloped cardamom agroforestry attract tourists for trekking and bird watching, students and researchers for various studies and research work	Enhancement of pollinator species	Sharma et al. (2007, 2019)
2.	Regulation of nutrient cycling	Livestock support by providing fodder	Sharma et al. (2007), Chauhan et al. (2013)
3.	Provision of sacred spaces for the different ethnic groups of the mountains	Conservation of germplasm and genetic resources of the native and heirloom crop species	Ramakrishnan (2001)
4.	Conservation of indigenous traditional knowledge of the locals	Provision of aesthetic and cultural services by providing ritual plants	Islam et al. (2017), Zhu et al. (2021)

15.4.3 *Cultural and Supporting Services*

Apart from the above-mentioned major services of the Himalayan agroforestry systems, it has been reported that these systems also provide supporting and cultural ecosystem services as well though to a lesser extent (Table 15.7). Some studies support evidence of services such as an increase in pollinator species (Sharma et al. 2020), provision of fodder for sustaining livestock, conservation of water, and enhancement of water use efficiency (FAO 2000; Chauhan et al. 2013), regulation of nutrient cycling, aesthetic value, and provision of ritual plants by the agroforestry systems of the Himalayan region (Sharma et al. 2007). Moreover, mountain landscapes including the agroforestry systems of the Himalayan region are believed to be sacred and culturally important for the different ethnic communities residing in the mountains (Ramakrishnan 2001) as they provide recreation and spiritual services thereby proving harmony and peace among the communities (Sharma et al. 2007). Further, the sloped forest-based cardamom agroforests of Sikkim Himalayas attract tourists for trekking and bird watching, students for research activities (Sharma et al. 2007) thereby providing cultural services to humans. Also, evidence of conservation of traditional knowledge and germplasm of native and heirloom crop and tree species, culturally important plants such as *Ocimum sanctum, Ficus reliogiosa*, *Thysanolaena maxima,* for some communities due to agroforestry systems have been reported (Islam et al. 2017).

15.5 Sustainable Development Goals (SDG) Through Agroforestry

The ability of the agroforestry systems to provide various services including the ecological and provisioning services to the humans led to conclude that type of agriculture can help in achieving some of the important goals of sustainable development (SDG) of the united nations. The united nations in 2015 drew 17 SDGs for the welfare of humanity. These systems have been reported to reduce poverty (SDG1), alleviate hunger (SDG2), have potential impacts on climate action (SDG13), biodiversity, responsible agricultural production (SDG15), and sustainable energy and land management (SDG7) which are important sustainable development goals (Mbow et al. 2014b; Do et al. 2016). Further, some of the Himalayan agroforestry systems such as large cardamom-based agroforestry of the Eastern Himalayas have been reported to increase good health and mental wellbeing (SDG 3) due to their close location to nature. Additionally, the expansion of agroforestry in the mountains leads to the enhancement of sustainability by providing food security, financial and livelihood improvement, improvement of soil fertility, and many more making this land-use system more acceptable and favourable.

15.6 Conclusions

This review provides substantial evidence that the agroforestry practices of the Himalayas play an important role in providing food and financial flow to the local community in addition to their regulating, supporting, and cultural services. Among the agroforestry systems reviewed, the subtropical and temperate agrihortisilvicultural system was the most productive in terms of financial flows and food security in comparison to the other agroforestry systems. However, other ecosystem services depending on various abiotic and biotic factors such as location, elevation, climatic conditions, geology and topography, edaphic factors, plant diversity, density, and species composition are provided by different agroforestry systems. It is evident that the Eastern Himalayan agroforests store more carbon than the western Himalayan. Overall, it can be concluded that the promotion of agroforestry practices will not only improve the livelihood options of the mountain people but they will also contribute towards the sustainability of the land use and above all livelihood security. The diverse benefits will also help in climate change mitigation and improvement of soil health and fertility of this region. We recommend future studies to explore the biophysical and socioeconomic benefits of the different agroforestry systems and climate risk adaptation by the Himalayan agroforestry managers.

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References

Arunachalam A, Chavan S, Handa A, Kumar A, Bhaskar S, Alagusunndaram K, Mohapatra T (2019) Agroforestry systems for the Indian Himalayan region. ICAR, New Delhi

Banyal R, Qaiser K, Abidi R (2016) Temperate agroforestry systems in Jammu and Kashmir. In: Gupta S (ed) Agroforestry for increased production and livelihood security. New India Publishing Agency, New Delhi, pp 41–59

Bhatt BP, Sachan MS (2004a) Firewood consumption along an altitudinal gradient in mountain villages of India. Biomass Bioenergy 27:69–75. https://doi.org/10.1016/j.biombioe.2003.10.004

Bhatt BP, Sachan MS (2004b) Firewood consumption pattern of different tribal communities in Northeast India. Energy Policy 32:1–6. https://doi.org/10.1016/S0301-4215(02)00237-9

Bhatt BP, Negi AK, Todaria NP (1994) Fuelwood consumption pattern at different altitudes in Garhwal Himalaya. Energy 19:465–468. https://doi.org/10.1016/0360-5442(94)90124-4

Bhatt BP, Rathore SS, Lemtur M, Sarkar B (2016) Fuelwood energy pattern and biomass resources in Eastern Himalaya. Renew Energy 94:410–417. https://doi.org/10.1016/j.renene.2016.03.042

Chaudhary S, Tshering D, Phuntsho T, Uddin K, Shakya B, Chettri N (2017) Impact of land cover change on a mountain ecosystem and its services: case study from the Phobjikha valley, Bhutan. Ecosyst Heal Sustain 3:1393314. https://doi.org/10.1080/20964129.2017.1393314

Chauhan SK, Dhillon WS, Singh N, Sharma R (2013) Physiological behaviour and yield evaluation of agronomic crops under agri-horti-silviculture system. Int J Plant Res 3:1–8

Chisanga K, Bhardwaj DR, Pala NA, Thakur CL (2018) Biomass production and carbon stock inventory of high-altitude dry temperate land use systems in North-Western Himalaya. Ecol Process 7:22. https://doi.org/10.1186/s13717-018-0134-8

Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260 de Silva T (1997) Industrial utilization of medicinal plants in developing countries. In: Bodeker G, Bhat K, Burley J, Vantomme P (eds) Medicinal plants for forest conservation and healthcare. FAO, Rome, pp 38–48

Deb S, Barbhuiya AR, Arunachalam A, Arunachalam K (2008) Ecological analysis of traditional agroforest and tropical forest in the foothills of Indian eastern Himalaya : vegetation, soil and microbial biomass. Trop Ecol 49:73–78

Do T, Catacutan D, Nguyen T (2016) Agroforestry for sustainable mountain management in Southeast Asia. Policy Brief no. 69. Agroforestry options for ASEAN series no. 3. Jakarta, Indonesia

FAO (2000) Global Forest Resources Assessment 2000

FAO (2015) Mapping the vulnerability of mountain peoples to food insecurity

Furtak K, Gałązka A (2019) Edaphic factors and their influence on the microbiological biodiversity of the soil environment. Adv Microbiol POSTĘPY Mikrobiol 58:375–384. https://doi.org/10.21307/PM-2019.58.4.375

Gautam DK, Bajracharya RM, Sitaula BK (2017) Effects of biochar and farm yard manure on soil properties and crop growth in an agroforestry system in the Himalaya. Sustain Agric Res 6:74–82. https://doi.org/10.5539/sar.v6n4p74

Goswami S, Verma K, Kaushal R (2013) Biomass and carbon sequestration in different agroforestry systems of a Western Himalayan watershed. Biol Agric Hortic 30:88–96. https://doi.org/10.1080/01448765.2013.855990

Goswami S, Verma KS, Kaushal R (2014) Biomass and carbon sequestration indifferent agroforestry systems of a Western Himalayan watershed. Biol Agric Hortic 30(2):88–96

Grêt-Regamey A, Brunner SH, Kienast F (2012) Mountain ecosystem services: who cares? Mt Res Dev 32. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1

Gupta SR, Dagar JC, Teketay D (2020) Agroforestry for rehabilitation of degraded landscapes: achieving livelihood and environmental security. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1. Springer, Singapore, pp 23–68

Hoermann B, Choudhary D, Choudhury D, Kollmair M (2010) Integrated value chain development as a tool for poverty alleviation in rural mountain areas: an analytical and strategic framework. ICIMOD, Kathmandu

Huang W, Luukkanen O, Johanson S, Kaarakka V, Räisänen S, Vihemäki H (2002) Agroforestry for biodiversity conservation of nature reserves: functional group identification and analysis. Agrofor Syst 55:65–72. https://doi.org/10.1023/A:1020284225155

IPCC (2001) Climate Change 2001: the scientific basis. In: Houghton JET, Ding Y, Griggs D, Noguer M, Van der Linden P, Dai X, Maskell M, Johnson C (eds) Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC), p 881

ISFR (2019) India State Forest Report. Forest Survey of India, Dehradun

Islam M, Quaiser K, Bhatt G (2017) Indigenous knowledge in traditional agroforestry systems of Kashmir valley: current challenges and future opportunities. Int J For Crop Improv 8:68–77

Jana B, Biswas S, Majumder M, Roy P, Mazumdar A (2009) Carbon sequestration rate and aboveground biomass carbon potential of four young species. J Ecol Nat Environ 1:15–24

Kalita R, Nath A (2016) Carbon stock and sequestration potential in biomass of tea agroforestry system in Barak Valley, Assam, North East India. Int J Ecol Environ Sci 42:107–114

Kanime N, Kaushal R, Tewari S, Raverkar K, Chaturvedi S, Chaturvedi OP (2013) Biomass production and carbon sequestration in different tree-based systems of Central Himalayan Tarai region. For Trees Livelihoods 22:38–50. https://doi.org/10.1080/14728028.2013.764073

Kashyap SD, Dagar JC, Pant KS, Yewale AG (2014) Soil conservation and ecosystem stability: natural resource management through agroforestry in Northwestern Himalayan region. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, pp 21–55

Kehie M, Khamu S (2018) Indigenous alder based farming practices in Nagaland, India: a sustainable agricultural model. J Tradit Folk Pract 5. https://doi.org/10.25173/jtfp.2017.5.2.75
Kherallah M, Delgado C, Gabre-Madhin E, Minot N, Johnson M (2002) The road half traveled: agricultural market reform in Sub-Saharan Africa. OCL Ol Corps Gras Lipides 9(6):416–425
Kumar M, Sharma CM (2009) Fuelwood consumption pattern at different altitudes in rural areas of Garhwal Himalaya. Biomass Bioenergy 33:1413–1418. https://doi.org/10.1016/j.biombioe.2009.06.003
Kumar A, Bisht P, Kumar V (2002) Traditional medicinal plants of Uttaranchal Himalayas. Asian Agrihist 6:167–170
Kumar GP, Murkute AA, Gupta S, Singh SB (2009) Carbon sequestration with special reference to agroforestry in cold deserts of Ladakh. Curr Sci 97:1063–1068
Kumar BM, Handa AK, Dhyani SK, Arunachalam A (2018) Agroforestry in the Indian Himalayan region: an overview. In: Gordon A, Newman S, Coleman BR (eds) Temperate agroforestry systems. CAB International, pp 152–172
Lepcha NT, Devi NB (2019) Carbon storage potential of a traditional cardamom agroforestry system of Sikkim Himalayas. Ecol Environ Conserv 25(4):321–327
Lepcha NT, Devi NB (2020) Carbon cycling and balance in a traditional cardamom based agroforestry system of Sikkim Himalayas. Trop Ecol 61:527–537. https://doi.org/10.1007/s42965-020-00110-9
Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol Evol 27:19–26. https://doi.org/10.1016/j.tree.2011.08.006
Maikhuri RK (1991) Fuelwood consumption pattern of different tribal communities living in Arunachal Pradesh in North-East India. Bioresour Technol 35:291–296. https://doi.org/10.1016/0960-8524(91)90127-6
Mavhura E, Manyena SB, Collins AE, Manatsa D (2013) Indigenous knowledge, coping strategies and resilience to floods in Muzarabani, Zimbabwe. Int J Disaster Risk Reduct 5:38–48. https://doi.org/10.1016/j.ijdrr.2013.07.001
Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014a) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr Opin Environ Sustain 6:8–14. https://doi.org/10.1016/j.cosust.2013.09.002
Mbow C, Van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014b) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67
Molden DJ, Vaidya RA, Shrestha AB (2014) Water infrastructure for the Hindu Kush Himalayas. Int J Water Resour Dev 30:60–77. https://doi.org/10.1080/07900627.2013.859044
Mukherji A, Molden D, Nepal S, Rasul G, Wagnon P (2015) Himalayan waters at the crossroads: issues and challenges. Int J Water Resour Dev 31:151–160. https://doi.org/10.1080/07900627.2015.1040871
Myers N, Mittermeler RA, Mittermeler CG, Da F, Gustavo AB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403. https://doi.org/10.1038/35002501
Nair PKR (1985) Classification of agroforestry systems. Agrofor Syst 3:97–128. https://doi.org/10.1007/BF00122638
Nath AJ, Sileshi G, Pathak K, Reang D, Nath A, Das A (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Prod 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831
Noble IR, Dirzo R (1997) Forests as human-dominated ecosystems. Science 277:522–525. https://doi.org/10.1126/science.277.5325.522
Osei WY (1993) Woodfuel and deforestation—answers for a sustainable environment. J Environ Manag 37:51–62. https://doi.org/10.1006/jema.1993.1004
Padma TV (2014) Himalayan plants seek cooler climes. Nature 512:359. https://doi.org/10.1038/512359a

Palacios Bucheli VJ, Bokelmann W (2017) Agroforestry systems for biodiversity and ecosystem services: the case of the Sibundoy Valley in the Colombian province of Putumayo. Int J Biodivers Sci Ecosyst Serv Manag 13:380–397. https://doi.org/10.1080/21513732.2017.1391879

Pandey R, Aretano R, Gupta AK, Meena D, Kumar B, Alatalo JM (2017) Agroecology as a climate change adaptation strategy for smallholders of Tehri-Garhwal in the Indian Himalayan Region. Small-Scale For 16:53–63. https://doi.org/10.1007/s11842-016-9342-1

Pandit B (2008) Study on socio-economic development of rural people through Agroforestry System in Rasuwa District of Nepal. Himalayan College of Agricultural Science and Technology, Kathmandu

Pandit VH, Thapa GB (2004) Poverty and resource degradation under different common forest resource management systems in the mountains of Nepal. Soc Nat Resour 17:1–16. https://doi.org/10.1080/08941920490247209

Pandit BH, Neupane RP, Sitaula BK, Bajracharya RM (2013) Contribution of small-scale agroforestry systems to carbon pools and fluxes: a case study from middle hills of Nepal. Small-Scale For 12:475–487. https://doi.org/10.1007/s11842-012-9224-0

Patiram (1994) Furrow application of lime is economical to rectify the acid soils of Sikkim. Indian Farming 5:21

Rajput BS, Bhardwaj DR, Pala NA (2017) Factors influencing biomass and carbon storage potential of different land-use systems along an elevational gradient in temperate northwestern Himalaya. Agrofor Syst 91:479–486. https://doi.org/10.1007/s10457-016-9948-5

Ramakrishnan PS (2001) Globally important ingenious agricultural heritage systems (GIAHS): an eco-cultural landscape perspective. http://ftp.fao.org/sd/SDA/GIAHS/backgroundpapers_ramakrishnan.pdf

Ramesh T, Manjaiah K, Mohopatra KP, Rajasekar K, Ngachan SV (2015) Assessment of soil organic carbon stocks and fractions under different agroforestry systems in subtropical hill agroecosystems of north-east India. Agrofor Syst 89(4):677–690. https://doi.org/10.1007/s10457-015-9804-z

Rao MR, Palada M, Becker BN (2004) Medicinal and aromatic plants in agroforestry systems. Agrofor Syst 61–62:107–122. https://doi.org/10.1023/B:AGFO.0000028993.83007.4b

Rawat YS, Vishvakarma SCR, Todaria NP (2009) Fuelwood consumption pattern of tribal communities in cold desert of the Lahaul valley, North-Western Himalaya, India. Biomass Bioenergy 33:1547–1557. https://doi.org/10.1016/j.biombioe.2009.07.019

Reid W, Mooney H, Cropper A, Capistrano D, Carpenter S, Chopra K (2005) Millennium ecosystem assessment. Ecosystems and human well-being: synthesis. Island Press, Washington DC, p 137

Roy PS, Kushwaha SPS, Murthy MSR, Roy A, Kushwaha D, Reddy CS, Behera MD, Mathur VB, Padalia H, Saran S, Singh S, Jha CS, Porwal MC (2012) Biodiversity characterisation at landscape level: national assessment. Indian Institute of Remote Sensing, Dehradun

Sayer J, Sunderland T, Ghazoul J, Pfund JL, Sheil D, Meijaard E, Venter M, Boedhihartono AK, Day M, Garcia C, Van Oosten C, Buck LE (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proc Natl Acad Sci U S A 110:8349–8356. https://doi.org/10.1073/pnas.1210595110

Sehgal JL, Mandal DK, Mandal C, Vedivelu S (1990) Agro-ecological regions of India. NBSS&LUP Publications, Nagpur

Shah G-M, Karki Nepal A, Rasul G, Ahmad F (2018) Value chain development of bay leaf in Nepal: an impact assessment. J Dev Eff 10:1–18. https://doi.org/10.1080/19439342.2018.1438494

Shah G-M, Ahmad F, Panwar S, Khadka MS, Ali A, Bisht S (2019) *Ocimum sanctum* [Tulsi]—an alternative additional livelihood option for the poor and smallholder farmers. Sustainability 11(1):227

Shanavas A, Mohan Kumar B (2003) Fuelwood characteristics of tree species in homegardens of Kerala, India. Agrofor Syst 58:11–24. https://doi.org/10.1023/A:1025450407545

Sharma E, Chettri N (2021) Biodiversity conservation and ecosystem services in the Hindu Kush Himalaya. J Graph Era Univ. https://doi.org/10.13052/jgeu0975-1416.911
Sharma G, Rai LK (2007) Climate change and sustainability of agrobiodiversity in traditional farming of the Sikkim Himalaya. In: ENVIS Proceedings, Gangtok, pp 193–218
Sharma R, Xu J, Sharma G (2007) Traditional agroforestry in the eastern Himalayan region: land management system supporting ecosystem services. Trop Ecol 48:1–12
Sharma G, Sharma E (2017) Agroforestry systems as adaptation measures for sustainable livelihoods and socio-economic development in the Sikkim Himalaya. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 217–243
Sharma A, Prasad R, Saksena S, Joshi V (1999) Micro-level sustainable biomass system development in central Himalaya: stress computation and biomass planning. Sustain Dev 7:132–139
Sharma E, Tse-Ring K, Chettri N, Shrestha A (2008) Climate change and its implications for mountain biodiversity in the Himalayas- trends, perception and impacts of climate change. In: Proc Int Mt Biodivers Conference, ICIMOD, Kathmandu
Sharma CM, Gairola S, Kumar M, Rawat Y, Bagwari HK (2009) Resource utilization in village ecosystem of temperate zone of Garhwal Himalaya. Indian J Agrofor 11:94–100
Sharma B, Rasul G, Chettri N (2015) The economic value of wetland ecosystem services: evidence from the Koshi Tappu Wildlife Reserve, Nepal. Ecosyst Serv 12:84–93. https://doi.org/10.1016/j.ecoser.2015.02.007
Sharma G, Hunsdorfer B, Singh KK (2016) Comparative analysis on the socio-ecological and economic potentials of traditional agroforestry systems in the Sikkim Himalaya. Trop Ecol 57:751–764
Sharma E, Molden D, Rahman A, Khatiwada YR, Zhang L, Singh SP, Yao T, Wester P (2019) Introduction to the Hindu Kush Himalaya assessment. In: Wester P, Mishra A, Mukherji A, Shrestha AB (eds) The Hindu Kush Himalaya Assessment: mountains, climate change, sustainability and people. Springer, Cham, pp 1–16
Sharma K, Acharya BK, Sharma G, Valente D, Pasimeni MR, Petrosillo I, Selvan T (2020) Land use effect on butterfly alpha and beta diversity in the Eastern Himalaya, India. Ecol Indic 110:105605. https://doi.org/10.1016/j.ecolind.2019.105605
Silici L (2014) Agroecology what it is and what it has to offer. IIED Issue Paper
Singh G, Rawat GS, Verma D (2010) Comparative study of fuelwood consumption by villagers and seasonal “Dhaba owners” in the tourist affected regions of Garhwal Himalaya, India. Energy Policy 38:1895–1899. https://doi.org/10.1016/j.enpol.2009.11.069
Singh AK, Arunachalam A, Ngachan SV, Mohapatara KP, Dagar JC (2014) From shifting cultivation to integrating farming: experience of agroforestry development in the Northeastern Himalayan region. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, pp 57–86
Singh M, Gupta B, Sarvade S, Awasthe RK (2015) Biomass and carbon sequestration potential in different agroforestry systems in Giri catchment of North-Western Indian Himalaya Biomass and carbon sequestration potential in different agroforestry systems in Giri catchment of North-Western Indian Himalaya. Indian J Agrofor 17:42–48
Singh M, Gupta B, Das SK (2018) Soil organic carbon density under different agroforestry systems along an elevation gradient in North-Western Himalayas. Range Manag Agrofor 39(1):8–13
Susila AD, Bambang S, Purwoko PMC, Kartika JG, Dahlia L, Wijaya K, Rahmanulloh A, Raimadoya M, Koesoemaningtyas T, Puspitawati H, Prasetyo T, Budidarsono S, Manue IK, Roshetko JM (2012) Vegetable-agroforestry systems in Indonesia. Bogor Agricultural University Indonesia, p 276
TEEB (2010) The economics of ecosystems and biodiversity: mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. The Economics of Ecosystems and Biodiversity, Malta
Torquebiau E (1985) Man-made dipterocarp forest in Sumatra. Agrofor Syst 2:103–127. https://doi.org/10.1007/BF00131269

Upadhyay TP, Sankhayan PL, Solberg B (2005) A review of carbon sequestration dynamics in the Himalayan region as a function of land-use change and forest/soil degradation with special reference to Nepal. Agric Ecosyst Environ 105:449–465. https://doi.org/10.1016/j.agee.2004.09.007

Vikrant K, Chauhan DS, Rizvi R (2018) Biomass and carbon potential in agroforestry systems along altitudes in Tehri District of Uttarakhand. Scientific Publishers

Vikrant K, Chauhan DS, Rizvi R (2020) Carbon stock assessment along altitudes in agrisilviculture systems of Tehri District, Uttarakhand, North-Western Himalaya—case study of Pratapnagar block. Indian For 146:202–207. https://doi.org/10.36808/if/2020/v146i3/144384

Xu J, Badola R, Chettri N, Chaudhary RP, Zomer R, Pokhrel B, Hussain SA, Pradhan S, Pradhan R (2019) Sustaining biodiversity and ecosystem services in the Hindu Kush Himalaya. In: Wester P, Mishra A, Mukherji A, Shrestha AB (eds) The Hindu Kush Himalaya Assessment: mountains, climate change, sustainability and people. Springer, Cham, pp 127–165

Xu S, Sheng C, Tian C (2020) Changing soil carbon: influencing factors, sequestration strategy and research direction. Carbon Balance Manag 15(2):1–9. https://doi.org/10.1186/s13021-020-0137-5

Yadav RP, Bisht JK, Bhatt JC (2017) Biomass, carbon stock under different production systems in the mid hills of Indian Himalaya. Trop Ecol 58(1):15–21

Zahoor S, Dutt V, Mughal A, Pala N, Qaisar KN (2021) Apple-based agroforestry systems for biomass production and carbon sequestration: implication for food security and climate change contemplates in temperate region of Northern Himalaya, India. Agrofor Syst 95:367–382. https://doi.org/10.1007/s10457-021-00593-y

Zhu M, Luo B, La B, Chen R, Liu F, Long C (2021) Homegarden agroecosystems managed by Salar people on Qinghai-Tibet Plateau. J Ethnobiol Ethnomed 17:20. https://doi.org/10.1186/s13002-021-00448-x

Chapter 16
Soil Biodiversity and Litter Decomposition in Agroforestry Systems of the Tropical Regions of Asia and Africa

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Abstract This chapter gives an overview of the agroforestry practices and their role in improving soil biodiversity, soil ecosystem functions and services, and litter decomposition processes in the agroforestry systems of sub-Saharan Africa and Asia. Agroforestry covers a complex set of practices, and for brevity, we follow the broad categories of agrisilvicultural, agrosilvopastoral, and silvopastoral systems. We discuss the diversity of soil fauna and microorganisms, which are found in the surface layer of soil, and underpin a wide range of soil ecosystem services that are essential to the sustainability of agroforestry systems. The increase in the diversity of soil macrofauna, soil microbial biomass, and microbial diversity in agroforestry systems is due to the ameliorative effects of trees, and greater organic matter inputs with variable litter quality. The improved micro-climate and a higher supply of organic residues generate higher earthworm diversity in tree-based systems. Moreover, a mix of plant species in agroforestry systems allows a larger diversity and abundance of mycorrhizal fungi than monocultures.

Through synthesis of several studies, we show that the diverse plant communities and structures can modify the important soil functions and with possible feedback to the above- and below-ground components of both trees and crops. Studies evaluated provisioning, regulation and maintenance, and cultural services provided by soils;

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several reviews and meta-analysis indicate the beneficial impact of agroforestry on soil ecosystem services including soil conservation, storage and cycling of nutrients, increasing infiltration rate and soil moisture content, improving soil biological quality, controlling diseases and pests, and sequestering atmospheric carbon dioxide.

The decomposition of litter in agroforestry system differs from that of natural forests and agricultural systems because of differences in the types and quality of organic residue inputs. We synthesized the literature on litter decomposition rates, mathematical models describing the pattern of litter decay, resource quality of litter, and the nutrient release patterns from decomposing litter in different types of agroforestry systems. In most studies, the single exponential mathematical model described the pattern of litter decomposition and nutrient release. The decomposition rate constants ($k = 0.37–8.92$ year^{-1}) for various litter species are found to be highly variable and often related to litter quality and climatic conditions. The tree species in both traditional and modern agroforestry systems having a combination of low- and high-quality litter show a highly variable nutrient release pattern from the decomposing litter. Agroforestry systems are highly efficient in improving soil biodiversity and litter decomposition processes leading to increase in the crop yield and sequestration of atmospheric carbon dioxide. However, there is a need for long-term studies on diversity of soil fauna, microorganisms, and litter decomposition for a better understanding of seasonal, short-term, and long-term effects of agroforestry practices.

Keywords Agroforestry practices · Soil fauna · Microbial diversity · Soil ecosystem functions · Soil ecosystem services · Decomposition rates · Nutrient release pattern · Litter quality

16.1 Introduction

The management of soil biodiversity and the soil ecosystem services are central to the sustainability of both natural and managed ecosystems (Kennedy and Gewin 1997; UNESCO-SCOPE 2007; Palm et al. 2007). Soil biodiversity is defined as the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes (FAO, ITPS, GSBI, SCBD and EC 2020). Soil organisms have a key role in the formation of soil organic matter (SOM), decomposition of organic residues, and detoxification of soil contaminants (Swift et al. 1979; Lavelle et al. 1994). Recently, some reviews have emphasized the importance of soil biodiversity in agroforestry systems (Barrios et al. 2012; Cardinael et al. 2020; Marsden et al. 2020). The effects of agroforestry systems on soil fauna abundance and diversity are positive when agroforestry is compared to cropland, and neutral or negative when compared to forests (Marsden et al. 2020).

It is now well recognized that the total biomass of soil organisms below ground equals or potentially exceeds that above ground. Soils harbour more than 25% of the earth's total biodiversity (Decaëns et al. 2006; Bardgett and van der Putten 2014). However, the soil biodiversity is under threat by land degradation, climate change, pollution, urbanization, and over-use and misuse of resources (Montanarella et al. 2015; Bach et al. 2020). Several organizations and programmes, including the Global Soil Partnership of the Food and Agriculture Organization, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), and the UN Convention on Biological Diversity have included soil biodiversity in their consideration of soils. The soil biodiversity in agroforestry systems can be managed sustainably by protecting multifunctional landscapes, restoring degraded ecosystems, and promoting sustainable agricultural practices. Besides, the farmers' perspectives and knowledge of soil biota and its integration with scientific knowledge contributes to a better understanding of tree–soil biota interactions in time and space for designing diverse cropping systems for supporting multiple functions and provision of ecosystem services (Swift et al. 2004; Giller et al. 2005; Barrios et al. 2012).

The decomposition of organic residues is crucial for the functioning of agroforestry system to facilitate the returns of nutrients to the soil, thereby reducing the input of chemical fertilizers, formation of soil organic matter and the maintenance of soil fertility. Studies on nutrient provisions in agroforestry systems have focused mostly on litter decomposition and release of nutrients from decomposing litter/pruning residues in relation to resource quality of litter, decomposer organisms and the environmental conditions (Lekha and Gupta 1989; Tian et al. 1992, 1995; Das and Das 2010; Teklay and Malmer 2004; Gnankambary et al. 2008; Negash and Starr 2021; Asigbaase et al. 2021). In tropical agroforestry systems, mixed residues of trees and crops with different resource qualities can potentially be used to manipulate residue decomposition to synchronize nutrient availability for plant growth (Sakala et al. 2000).

This chapter gives an overview of the agroforestry practices and their role in improving soil biodiversity, soil ecosystem functions and services, and litter decomposition processes in the agroforestry systems with emphasis on sub-Saharan Africa and Asia.

16.2 Agroforestry Practices

Agroforestry is any land-use system, practice or technology, where woody perennials are integrated with agricultural crops and/or animals in the same land management unit, in some form of spatial arrangement or temporal sequence (Lundgren and Raintree 1983). Agroforestry is a dynamic, ecological-based, natural resource management system that through integration of trees on farms and in agricultural landscape, diversifies and sustains production of agricultural and its related commodities for increased social, economic and environmental benefits for land users at all levels. An agroforestry practice is a distinctive arrangement of components in space and time; and an ecologically-based classification of agroforestry practices is rooted in the role of trees in agricultural landscape (Mbow et al. 2014).

In Asia and Africa, agroforestry covers a complex set of practices, and there are multiple ways of classifying these practices. For brevity, we will follow the definition and typology of the three categories identified by Shin et al. (2020) in the Asia-Pacific region and globally by Nair (1985) and Nair et al. (2021). Accordingly, the three broad categories of agroforestry systems are (1) agrisilvicultural, (2) agrosilvopastoral, and (3) silvopastoral systems. Agrisilviculture is defined as integrating trees with cropping, while silvopasture is an integrated system of trees and pastures and/or livestock, and agrosilvipasture is a tree-integrated system with livestock/pasture and crops together. Home gardens are complex agroforestry systems comprised of intimate, multi-story combinations of various trees, shrubs and crops around homesteads. Home gardens are one of the oldest forms of agroforestry practice characterized by high diversity and complexity of plant species structure and efficient nutrient cycling (Das and Das 2010). For example, the home gardens in Chengamanad, Kerala, India, have four strata as shown in Fig. 16.1a. Plantation crop combinations, multilayer forest gardens, intercropping systems, windbreaks and shelterbelts, are other common agroforestry practices. Silvopastoral systems include various practices like trees on rangeland or pastures, protein banks, and plantation crops with pastures and animals (see Nair et al. 2021)

The prominent South Asian agroforestry systems include parkland systems; agrisilviculture involving poplar (*Populus deltoides*) and Eucalyptus spp.; plantation agriculture involving *Coffea* spp., *Camellia sinensis*, cacao, and spices in association with a wide spectrum of trees, betel vine + areca palm; intercropping systems with coconut, *Hevea brasiliensis*, and other trees. According to Bagyaraj et al. (2015), Kodagu district is the largest coffee growing region in India, producing about 38% of India's coffee with the production area concentrated in the Western Ghats (Garcia et al. 2007, 2010) and was found to be an interesting site for a detailed study on soil biodiversity.

Prosopis cineraria is commonly protected in fields (planted with millet, wheat and legumes), also occurs on fallows and grazing lands in the semi-arid zone of Rajasthan, India. This agroforestry practice has been found beneficial for improving soil microbial diversity, particularly that of the arbuscular mycorrhizal fungi (Verma et al. 2008). *Eucalyptus tereticornis* and *Populus deltoides* are being extensively used in agroforestry in India on irrigated agricultural lands in Indo-Gangetic plains and outer plain of Uttaranchal and Himachal Pradesh. These agrisilvicultural agroforestry systems enhance carbon storage in soil and the woody biomass, and can play an important role in carbon sequestration for soil, improving soil health together with climate change mitigation (Saini and Gupta 2017; Gaur and Gupta 2012; Rizvi et al. 2011; Rizvi et al. 2020; Dagar et al. 2020a, b). The agroforestry systems of *Populus deltoides* with wheat crop, and clonal *Eucalyptus tereticornis* with sugarcane crop at Kurukshetra and Yamunanagar, in northern India are shown in Fig. 16.1.

Throughout Africa, agroforestry systems are found in a wide variety of shapes and forms. Many of these systems have little more in common than the coincidence of woody perennials with agricultural crops and/or livestock (Mbow et al. 2014; Dagar et al. 2020a, b). Some of the common agroforestry practices found in different regions of Africa include shifting cultivation, Taungya and Shamba systems,

Fig. 16.1 The diversity of agroforestry practices: (**a**) A rural home garden in Kerala (Photo: B. Mohan Kumar); (**b**) Shaded coffee in the Western Ghats (Photo: B.Mohan Kumar). (**c**) *Populus deltoides* with wheat crop and (**d**) clonal *Eucalyptus tereticornis* with sugarcane crop in the north-western India (Photo; SR Gupta and R Saini); parklands' with *Faidherbia albida* in Sahel (Photo: Chris Reij) (**e**); and with the crop is maize (*Zea mays*), *Vitellaria paradoxa* (**f**) in Dano, Southwestern Burkina Faso (Photo: Dimobe Kangbeni)

rotational woodlot system, improved tree fallows, home gardens, parkland systems and silvopastoral systems (Dagar et al. 2020a, b). Typically, agroforestry practices are multifunctional, although the type and magnitude of the goods and services produced vary greatly depending on the components involved and their management in the landscape (Kuyah et al. 2020). In parklands, wide range of tree species are often grown in random spacing in cropped fields, these constitute the largest single agricultural land use in sub-Saharan Africa. Some parklands are mono-specific (e.g. *Faidherbia albida* and *Borassus aethiopum*-based), but others have dominant tree species mixed with a range of tree and shrub species (Bayala et al. 2014). In some instances, the original species such as *Prosopis africana, Vitellaria paradoxa, Faidherbia albida* and *Parkia biglobosa* are retained, while cash plantations such as oil palm (*Elaeis guineensis*) are introduced in others (e.g. *Adansonia digitata*). A view of parklands' with *Faidherbia albida* and with *Vitellaria paradoxa* in the West African Sahel shows the presence of dispersed trees in crop fields (Fig. 16.1e, f).

Several species such as *Leucaena leucocephala, Gliricidia sepium, Cajanus cajan, Flemingia macrophylla, Inga edulis, Senna siamea, S. spectabilis, Calliandra calothyrsus, Alchornea cordifolia, Sesbania grandiflora, S. sesban, Erythrina variegata, E. indica,* and *E. poeppigiana* have been tested as hedgerow species in different parts of the tropics (see Dagar et al. 2020a, b).

Intercropping of fertilizer trees with cereal crops is an improvement building on the characteristics and advantages of alley cropping, but minimizes the 'hedge effect', competition and tree management (Akinnifesi et al. 2006, 2010). The best-known example is the *Gliricidia*-maize intercropping in Malawi and Zambia (Sileshi et al. 2020a). For instance, in a long-term trial at Makoka in Malawi, Akinnifesi et al. (2006) showed that *Gliricidia* intercropping with maize increased maize yield in the range of 100–500%, averaging 315% over a 10 year-period. In this study, the increase in yield was more evident in the third year after tree establishment and onwards.

16.3 Soil Fauna and Microbial Diversity

Soil biota comprises mainly of soil fauna and microbes found in the surface layer of soil, are highly diverse and underpin a wide range of ecosystem services that are essential to the sustainability of both natural and managed ecosystems (Barrios 2007; Barrios et al. 2012; Lavelle et al. 2006; Wu et al. 2011). The soil biota directly influences soil fertility by mobilizing nutrients and form soil structures, increasing water infiltration and soil carbon storage, and decreasing soil erosion. Maintaining active soil invertebrate communities in soils would considerably improve sustainability of agroforestry practices through regulation of soil processes at different scales of time and space (Sileshi and Mafongoya 2007). There are three types of interacting factors that influence the diversity and activity soil organisms, and the litter decomposition process: (a) physico-chemical environment; (b) litter quality; and (c) soil fauna and soil microbial activity and diversity (Fig. 16.2).

Temperature and moisture are the two important abiotic factors controlling the rate of decomposition under natural conditions (Singh and Gupta 1977), whereas soil conditions affect the activity of soil organisms which indirectly affect litter decomposition rates. Leaf litter quality refers to the suitability of the substrate as a carbon, energy or nutrient source to the organisms that degrade it (Singh and Gupta 1977;

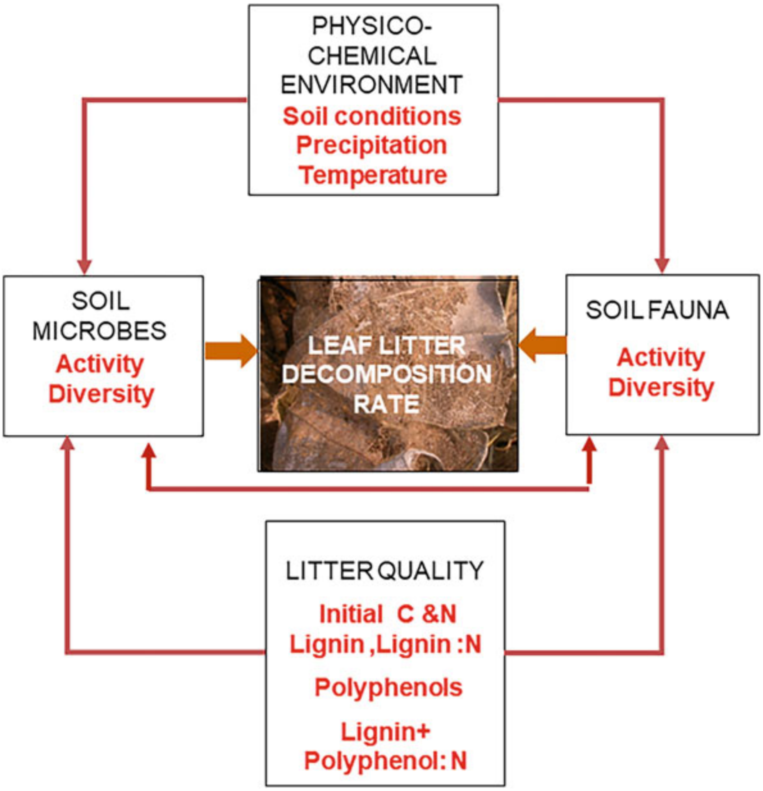

Fig. 16.2 The main factors that control soil biodiversity and litter decomposition rate. (Adapted from Prescott et al. 2000)

Swift et al. 1979). The soil biota is of decisive importance in decomposing organic residues from both aboveground and belowground parts of plants in the soil.

16.3.1 Diversity of Soil Fauna

On the basis of size, there are three groups of soil fauna, viz., microfauna (protozoa and nematodes in water filled soil porosity), meso-fauna (collembola and acarids of litter and air-filled pore space in soil), and macrofauna (termites, earthworms and large arthropods) (Swift et al. 1979). The major guilds of soil invertebrates, i.e., micro foodwebs, litter transformers and ecosystem engineers have been recognized on the basis of their interaction with soil microorganisms and the type of excretory products (Lavelle 1997). Earthworms and termites, which are recognized as 'ecosystem engineers' (Jones et al. 1994), incorporate considerable amount of organic

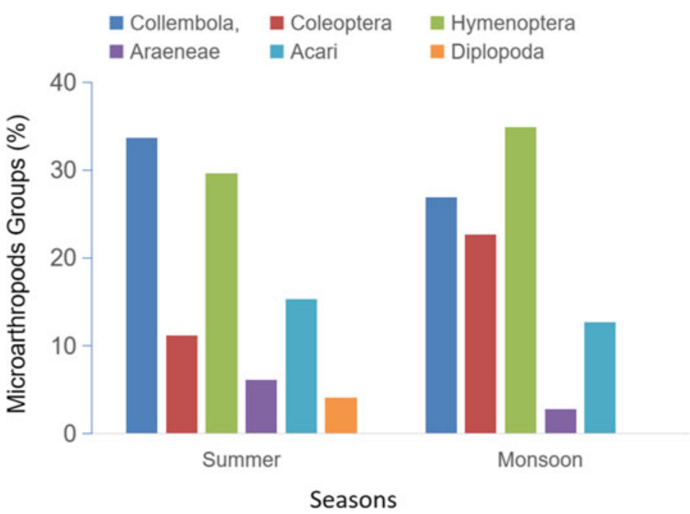

Fig. 16.3 Distribution of different groups of soil microarthropods (%) during summer season and monsoon season in home garden of a village in Kerala, India. (Based on Lakshmi and Joseph 2017)

matter into their casts and physically protect it from microbial breakdown (Six et al. 2004; Ayuke et al. 2011). Termites are known to be efficient in cellulose and lignified subsystems as they produce a variety of enzymes due to the presence of associated microflora and protozoan in their guts to digest cellulose, lignin and other components (Lee and Wood 1971).

For different agroforestry systems in Africa and Asia, a number of workers have suggested that the agroforestry and conservation farming lead to improvement of soil biodiversity. For example, mulching effects on diversity of soil fauna (Tian et al. 1993), diversity of nematodes (Kimenju et al. 2004), abundance and biomass of earthworms (Okwakol and Sekamatte 2007; Sileshi and Mafongoya 2006b; Tian et al. 2000; Mulia et al. 2021; Kamau et al. 2017, 2020), and various arthropods and other types of fauna (Adejuyigbe et al. 1999; Sileshi and Mafongoya 2006b; Kamau et al. 2017), and soil microarthropods (Lakshmi and Joseph 2017, 2020).

In home garden soils of Kerala, India, studies have represented soil microarthropods by six groups including Acarina, Collembola, Protura, Pauropoda, Diplura and Symphyla; Acarina and Collembola being most abundant (Lakshmi and Joseph 2017, 2020). In these observations, the occurrence of these microarthropods was positively correlated to soil moisture and organic carbon, and had negative correlation to soil temperature and soil pH. The abundance of the six groups of microarthropod ranged from 33.67% of Collembola to 4.08% of Diplopoda in summer; the five groups of soil fauna varied between 34.91% of Hymenoptera to 2.83% of Araeneae during monsoon months (Fig. 16.3). Based on the presence of eu-edaphic and epi-edaphic microarthropod fauna, a soil quality index was derived which indicated that 2 home gardens were of good quality, 21 were of medium quality and 2 were of poor quality (Lakshmi and Joseph 2017).

Table 16.1 Effect of length and type of practices on soil macrofauna at Msekera, eastern Zambia (Sileshi and Mafongoya (2006a)

Length of practice	Type of practice (sample size)	Number of orders	Total fauna
Ten years	Coppicing fallow (24)	3.7	300
	Maize without fertilizer (12	2.8	818.7
	Maize with fertilizer (12)	1.6	222.7
Five years	Coppicing fallow (24)	2.8	261.3
	Maize without fertilizer (12	1.9	122.7
	Maize with fertilizer (12)	1.2	65.8
Two years	Mixed species fallow (23)	4.0	331.1
	Coppicing fallow (24)	2.9	209
	Non-coppicing fallow (8)	2.6	120.0
	Maize without fertilizer (8)	2.0	128.0
	Maize with fertilizer (8)	1.8	98.0

Sileshi and Mafongoya (2006a, b) compared the population of soil macrofauna after 5, 7, and 12 years of planting maize in monoculture, and maize grown in legume fallows (*Gliricidia sepium, Leucaena leucocephala, Leucaena diversifolia, Sesbania sesban* and *Acacia angustissima*) in smallholder agriculture in southern Africa. In this study, the maize grown in legume fallows had more numbers of invertebrate orders per sample and the total macrofauna (all individuals per square metre) than monoculture maize (Table 16.1). Particularly, the earthworm populations under maize grown in *Gliricidia sepium* fallows were significantly higher than those under fully fertilized monoculture maize (Sileshi and Mafongoya 2006b). The majority of the soil invertebrates showed higher abundance under maize grown in legume fallows because of the availability of a year-round canopy and improvement of soil microclimate.

Studies by Sileshi and Mafongoya (2007) in Zambia showed that soil biota responded differently to the application of organic resources of different quality. While earthworms and beetles were more abundant under legumes producing fast decomposing "high-quality" biomass, millipedes predominated under legumes producing slow decomposing "low-quality" biomass, and spiders and centipedes were not influenced by biomass quality. These observations suggest that the diverse plant communities and structures in agroforestry system can modify the important soil functions, and with possible feedback to the above- and below-ground components of the agroforestry itself and accompanying commodity crops.

In an analysis by Barrios et al. (2012), agroforestry systems consistently generated substantial increases in the mean abundance of all groups of soil fauna compared to the continuous cropping control (Table 16.2). The response ratio (RR), the ratio of the mean value of the agroforestry practice to that of the control (continuous cropping), was used to compare different soil biota in soils under agroforestry and continuous cultivation without trees (Barrios et al. 2012). While, agroforestry systems consistently showed marked increases in the mean abundance of soil organisms, some groups of soil fauna indicated greater response than others. For

Table 16.2 Comparison of mean densities (individuals per m^2) of different soil biota in soils under agroforestry and continuous cultivation without trees, with the calculated response ratios (RR) (Adapted from Barrios et al. (2012) and references therein)

	Agroforestry	Monocrop	RR[a]
Soil macrofauna			
Earthworms	54.4	17.6	3.1
Beetles	20.9	9.6	2.2
Centipedes	2.7	0.5	5.6
Millipedes	8.1	1.3	6.1
Termites	90.7	81.0	1.1
Ants	23.2	8.6	2.7
Soil mesofauna			
Collembola	3890.1	2000.7	1.9
Mites	5100.7	1860.1	2.7
Soil microfauna			
Non-parasitic nematodes	2922	1288	2.3
Parasitic nematodes	203.7	211.5	1.0

[a] The response ratio (RR), is the ratio of the mean value of the agroforestry practice to that of the control (continuous cropping). If trees do not have any effect on abundance RR = 1; if agroforestry trees favour soil biota the value of RR will be larger than 1, and vice versa if trees do not favour soil biota

example, millipedes and centipedes with RR near six appeared to benefit most from trees, followed by earthworms, ants, and mites with RR near three, springtails and beetles with RR near two. Termites and parasitic nematodes with RR near one seem to be largely unaffected.

The spatial arrangement of trees within farms has been shown to play a key role in determining the patterns of soil macrofauna distribution (Kamau et al. 2017). While, the tree species and the distance from trees had a significant effect on soil macrofauna abundance in relation to the duration of cultivation in several farms along the Kakamega-Nandi Forest complex in Kenya. In this study, higher soil macrofauna abundance was found after 16 and 62 years of cultivation under the canopy of *Croton megalocarpus*, *Eucalyptus grandis* and *Zanthoxylum gilletii,* and it was dependent on tree species (Table 16.3). Moreover, the average Earthworm abundance across the tree zones was highest below the canopy of *Z. gilletii* averaging 338.35 individuals m^{-2}, compared to 11.33 individuals m^{-2} after 10 years of cultivation under the same tree (Table 16.3). Beetles showed higher numbers under *E. grandis* and *C. megalocarpus* than under *Z. gilletii*, although the duration of cultivation had no significant influence (Table 16.3). Thus, a diverse tree cover is required in agricultural landscapes to conserve soil macrofauna communities and the contribution of their activity to soil ecological functions (Kamau et al. 2017).

There is sufficient evidence to show the beneficial effects of alley cropping on soil fertility maintenance under high base status soils (Kang and Ghuman 1991; Dagar 1995; Dagar et al. 2020a, b), and for controlling soil erosion (Young 1989; Lal 1989; Dagar et al. 2014a, b, 2020a, b). The substrate quality factors such as C/N ratio, lignin, and to lesser extent polyphenol contents determine the decomposition and

Table 16.3 Soil macrofauna abundance (mean individuals m^{-2} across tree zones) as influenced by the duration of cultivation, tree species in the Kakamega-Nandi Forest complex in Kenya (derived from Kamau et al. 2017)

	Croton megalocarpus			*Eucalyptus grandis*			*Zanthoxylum gilletii*		
	10 yearr	16 years	62 years	10 years	16 years	62 years	10 years	16 years	62 years
Ants	17.98	46.33	15	38.33	38.33	11.35	8.68	12	9.68
Beetles	35.68	51.3	43.33	35.33	35.33	34.33	19.68	29	28.33
Earthworms	19.68	83.65	144	28.35	28.35	115.03	11.33	338.35	160.68
Termites	28	77.98	28.2	8.68	8.68	11.33	15.68	28.1	3.98
Others	8.7	24.96	16.8	6.03	12.33	8.3	9.83	17.29	9.28

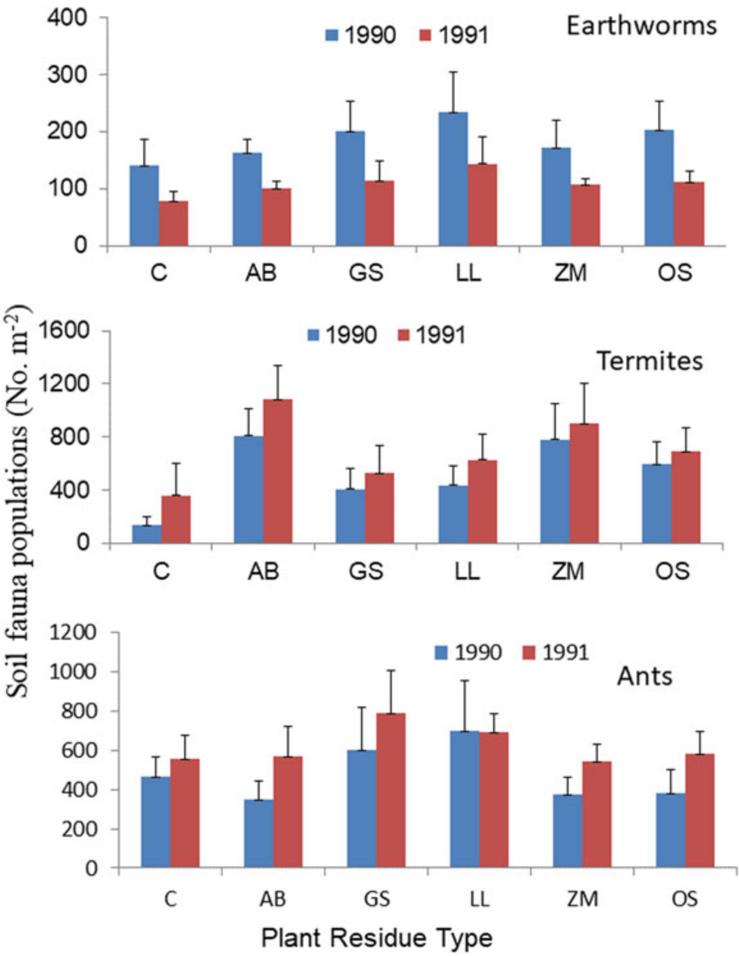

Fig. 16.4 Soil fauna populations (No. m^{-2}) (X + SE)' within soil layer of 0–30 cm after mulching with five types of plant residues. C = control; AB = *Acioa barteri*; GS = *Gliricidia sepium*; LL = *Leucaena leucocephala*; ZM = (*Zea mays*) stover; OS = (*Oryza sativa*) straw. (Based on Tian et al. 1993)

nutrient-release patterns of the pruning (Kang 1993). Tian et al. (1993) investigated the effect of *Acioa barteri, Gliricidia sepium* and *Leucaena leucocephala* prunings, maize (Zea *mays)***,** stover, and rice (*Oryza sativa)* straw as mulch on soil fauna under humid tropical conditions. In their study extending for a period of 2 years, there was increase in mean soil population of Earthworm by 41%, termite population by 177% and ant populations by 36%, higher under *Leucaena* and *Giiricidia* pruning (Fig. 16.4). Moreover, *Acioa* mulch and Maize stover supported the highest termite population (Fig. 16.4). While, N and lignin contents of organic residues were found to play a key role in faunal abundance in the soil through their effect on palatability and decomposability (Tian et al. 1993).

16.3.1.1 Abundance and Diversity of Earthworms in Agroforestry

Earthworms can be used as an integrative measure of soil health, assuming their importance in regulating soil processes which are vital to the continued formation of soil and as protection against soil degradation. Earthworms convert plant residues into soil organic matter by increasing residue exposure to microbial activity and feeding on soil organic matter (Lee 1985). Improved micro-climate in agroforestry, e.g., lower soil temperature and higher soil humidity, tillage, and a higher supply of organic residues generate higher earthworm diversity in tree-based systems (Tian et al. 2000). Agroforestry systems have been shown to increase abundance, biomass and diversity of earthworms compared to crop monocultures (Price and Gordon 1999; Rahman et al. 2012; Cardinael et al. 2019). In tropical regions of Asia and Africa, the population and diversity of earthworms vary across land habitats due to variation in soil moisture, soil temperature, soil properties, vegetation types, and land use management (Bhadauria and Ramakrishnan 1989; Julka and Paliwal 2005; Singh et al. 2015; Rajkhowa et al. 2015; Kamau et al. 2017; Mulia et al. 2021).

A high diversity of earthworm fauna has been reported in India due to varied climate and availability of diverse ecological niches (Julka and Paliwal 2005). A total of 413 species and subspecies of earthworms, belonging to 69 genera and 10 families are found in different biogeographical region of India; the eastern Himalayan Ago-climate zone exhibits high earthworm diversity accounting for 26% of all the species found in India (Julka and Paliwal 2005). The conversion of native forest by shifting agriculture has shown decline in species richness of earthworms in western Orissa, India (Senapati et al. 2005). In the Nilgiri biosphere reserve of the Western Ghats in India, Rahman et al. (2012) found significantly higher abundance of earthworms in agroforestry systems and forest ecosystems than in annual crop fields. They also found the highest diversity of earthworms in semi-evergreen forests followed by moist deciduous forest and agroforestry systems.

According to Mulia et al. (2021), the conversion of natural forests to different land uses in the two buffer-zone communes of Song Thanh Nature Reserve in Vietnam has been found to reduce earthworm diversity which can substantially affect soil health and ecosystem functions in the two communes. According to their study, higher earthworm diversity was found in tree-based farming systems, like agroforestry and planted forests. In their study, *Pontoscolex corethrurus* was omnipresent, particularly in dominated human-disturbed habitats which may bring unfavourable impacts such as soil compaction and pose a threat to native earthworm species. Therefore, to avoid the further decline of earthworm diversity and rampant expansion of *P. corethrurus* in the two study communes, the study indicated an urgent protection of the remaining natural and regenerated forests, and suggested promotion of tree-based farming systems, such as agroforestry to reconcile earthworm conservation and local livelihoods (Mulia et al. 2021).

In smallholder agroforestry systems of South Nandi Kenya, Kamau et al. (2020) reported the spatial variations in the influence of three dominant trees (*Croton megalocarpus*, *Eucalyptus grandis* and *Zanthoxylum gilletii*) on soil aggregation and carbon content. These differences were attributed to the high number of endogeic earthworm species, *Nematogenia lacuum* (Ocnerodrilidae) in soils under the canopy of *Z. gilletii* trees. Moreover, there was greater abundance of small macroaggregates and microaggregates in soils under the canopy of *Z. gilletii* with an average weight of 62.8 g and 9.4 g 100 g^{-1} of soil compared to 53.9 g and 3.1 g 100 g^{-1} in soils under *C. megalocarpus,* and 48.7 g and 3.9 g 100 g^{-1} in soils under *E. grandis*, respectively.

16.3.2 Diversity and Activity of Soil Microorganisms

Soil microorganisms including bacteria, fungi and actinomycetes show greater taxonomic and functional diversity. Soil fungi convert organic substrate to form new cells more efficiently as compared to bacteria and may favour carbon sequestration in agricultural systems (Holland and Coleman 1987). The soil microbial activity includes measures of the respiratory activity of soil organisms (Singh and Gupta 1977), soil microbial biomass (Vance et al. 1987) and microbial respiration (Ingram et al. 2005). In terrestrial ecosystem, carbon dioxide evolution from the soil provides a useful parameter for studying soil biological activity and carbon cycling (Singh and Gupta 1977). While soil microbes have the capacity to use pools of metabolizable carbon contained in the soil, which is stimulated easily by soil amendments and litter inputs in agroforestry systems.

The soil microbial biomass is the collective mass of all soil micro-organisms including bacteria, fungi and protozoa (Jenkinson and Ladd 1981), which comprises 1–5% of total organic carbon in soil and acts as a source and sinks for plant nutrients (Singh et al. 1989). Soil microbial biomass is a sensitive indicator of soil quality and plays a key role in plant residue decomposition, nutrient conservation and cycling processes (Powlson et al. 1987; Wang et al. 2008). In several studies, soil microbial biomass and microbial diversity were found to be greater in the agroforestry systems due to the ameliorative effects of trees and organic matter inputs and the differences in litter quality and quantity, and root exudates (Kaur et al. 2000, 2002a, b; Mungai et al. 2005). For example, in tree plantations and silvopastoral agroforestry systems raised on sodic soils in north western India, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land use type (Kaur et al. 2000), and tree species (Kaur et al. 2002b). In a study on silvopastoral systems, the soil organic matter was positively correlated with microbial biomass carbon, soil nitrogen, and nitrogen mineralization rates ($r = 0.95–0.98$, $p < 0.01$) (Kaur et al. 2002a, b).

In a subtropical climate in Southern Yunnan, Rigal et al. (2020) studied the effect of three shade tree species (*Cinnamomum camphora*, *Bishofia javanica*, and *Jacaranda mimosifolia*) on soil enzyme activities, soil microbial communities, and nematode communities. In their study, the total microbial communities were 34% more abundant in shaded inter-row than in open inter-rows (+7.7 ± 2.4 nmol g^{-1}), and 64% more abundant under shaded coffee rows than under open coffee rows (+13.0 ± 3.8 nmol g^{-1}) especially during the dry season, and a significant build-up of soil organic matter under shaded coffee.

According to Tangjang et al. (2015), there were seasonal and depth-wise variations in bacterial and fungal populations under *Areca catechu*-based traditional homestead garden of north east India; 24 soil micro-fungal forms were recorded from the three study sites. Moreover, the plant species composition, plant residues and organic matter and soil mineral nutrients affected microbial populations and their species composition.

Molecular studies investigating microbial communities or functional genes in soils of agroforestry systems have been investigated by only a few workers (e.g. Udawatta et al. 2008; Beule et al. 2019; Beule et al. 2020). Among these studies, Udawatta et al. (2008) found that total soil-extractable DNA, used as a proxy for soil microbial biomass, was higher in agroforestry than in cropland and grassland. However, the use of taxon-specific PCR assays to assess differences in soil microbial communities between the tree and crop rows could be useful for understanding functional soil microbial diversity (Udawatta et al. 2008). Another study on temperate agroforestry cropland and grassland showed increased fungi-to-bacteria ratio under trees, and alterations of ammonium-oxidizing populations (Beule et al. 2019). Tree litter input (leaves, twigs, roots) and persistent tree roots are reported to stimulate soil microflora under the trees. In a study on temperate agroforestry systems, Poplar rows increased the abundance of several soil bacterial and fungal groups as compared to the crop rows of agroforestry and monoculture croplands (Beule et al. 2020). However, there is need to combine the real-time PCR with soil process measurements for a better understanding of the microbial regulation of key soil functions in agroforestry systems (Beule et al. 2020).

16.3.3 Diversity of Arbuscular Mycorrhizal (AM) Fungi

Arbuscular mycorrhizal (AM) fungi help in maintaining soil structure, soil quality and various ecological interactions in soil. Mixtures of plant species in agroforestry systems usually allow a larger diversity and/or abundance of mycorrhizal fungi than monocultures (Cardoso and Kuyper 2006). Recently the diversity of AM fungi has been extensively studied in agroforestry coffee system as compared to monocultural coffee plantation soils in Bonga natural coffee forest of south-western Ethiopia (Muleta et al. 2007, 2008), while Bagyaraj et al. (2015) carried out a detailed study on soil biodiversity including AM fungi in different coffee agroforestry management in the Western Ghats of India. Here, we are describing findings of a few important studies in sub-Saharan Africa and Asia.

In the study of Cardoso et al. (2003), the vertical distribution of AM spores under agroforestry (shaded) and monoculture coffee (unshaded) systems showed greater number of AM spores in the soil layers of agroforestry systems than in monocultural coffee plantation soils. Muleta et al. (2008) found significantly higher AM fungal spore densities in agroforestry coffee systems as compared to compared to monocultural coffee system in the 0–30 cm soil layer. While, significantly higher AMF spore densities were recorded at canopy bases and at 0–30 cm soil depth. Glomus (31.2%) followed by *Acaulospora* (26.7%) dominated at all sites in smallholder agroforestry and monocultural coffee systems in south-western Ethiopia (Muleta et al. 2008). The abundance of other genera was: *Scutellospora* (15.8%), *Gigaspora* (14.0%) and *Entrophospora* (5.5%). In the study of Muleta et al. (2007), agroforestry practices including the use of leguminous shade trees effectively maintained AMF numbers in soils. They reported that the leguminous shade trees in coffee in Bonga natural coffee forest increased mycorrhizal populations compared to non-leguminous trees; legumes are more dependent on AM fungi than non-legumes.

Bagyaraj et al. (2015) investigated soil bacteria, fungi, actinomycetes and arbuscular mycorrhizal (AM) fungi in Arabica and Robusta coffee agroforestry management systems in the Western Ghats, India. In this study, population of bacteria, fungi and actinomycetes were higher under evergreen ecosystems compared to that of deciduous conditions. The AM colonization was found to be significantly higher (66.7%) in Arabica coffee grown under 3 or more shade tree species in the deciduous ecosystem. In case of evergreen ecosystem, the highest per cent AM colonization was recorded in Robusta coffee under 3 or >3 shade tree species (59.7%). The Arabica coffee system harboured more AM fungi, bacterial population, N fixers, whereas Robusta coffee system exhibited higher number of fungi and actinomycetes.

Hailemariam et al. (2013) studied spore abundance, and root colonization of indigenous agroforestry trees species (*Albizia gummifera* and *Croton macrostachyus)* in the rift valley, Ethiopia. In this study, the number of spore count was significantly higher under the canopy of *A. gummifera* trees (791 spores per 100 g of dry soil) and *C. macrostachyus* (877 spores per 100 g of dry soil) than outside the canopy of trees (547 and 588 spores per 100 g of dry soil). Further, the study suggested that the rhizospheres of indigenous agroforestry tree species are important source of inoculum for the maize crop and can play an important role in the maintenance of soil fertility.

There was significant effect of crop type on AM fungal diversity, being greater in *Populus deltoides* + sugarcane systems (47 AMF species) as compared to that of *Populus deltoides* + wheat systems (35 AMF species) in northern India (Saini and Gupta 2018). In the study of Saini and Gupta (2018), the AM fungi isolated from the rhizosphere soils of wheat and sugarcane in the agroforestry systems belonged to five genera, i.e., *Acaulospora*, *Entrophospora*, *Glomus*, *Gigaspora* and *Sclerocystis*; the species of *Glomus* and *Acaulospora* were most abundant. The AM root colonization (seen as formation of arbuscules and formation of round and globose vesicles with attached hyphae) in sugarcane at 15–30 cm soil depth was greatest (91.0–96.2%), growing under 1- and 2-year-old *Populus deltoides* agroforestry system (Fig. 16.5). Moreover, the percentage of AMF root colonization of wheat

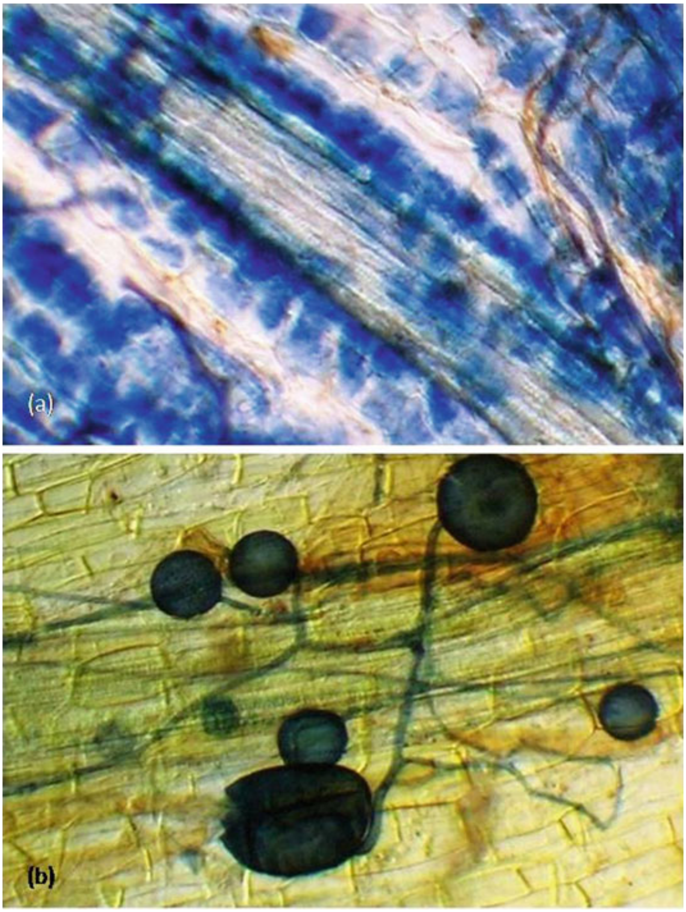

Fig. 16.5 Arbuscular mycorrhizal infection in sugarcane roots showing (**a**) formation of arbuscules with mycorrhizal hyphae in root cortical cells; (**b**) formation of round and globose vesicles with attached hyphae (100×). (From Saini and Gupta 2018)

up to 30 cm soil depth in the agroforestry systems was greatest in the 6 year old *Populus deltoides* + wheat systems (32.4–92.2%).

In *Acacia nilotica* and *Salvadora persica* silvopastoral system on saline-sodic soils, in north western India, the AM root colonization in various grass species (*Cenchrus ciliaris, Panicum miliare, Brachiaria reptans, Desmostachya bipinnata, Dichanthium annulatum)* varied from 47.8% to 71.2% (Kumari et al. 2018). In the agrohorticultural system of *Carissa carandas* along with *Hordeum vulgare*, Kumari et al. (2018) recorded some 23 species of mycorrhizal fungi belonging to *Glomus*, *Acaulospora,* and *Gigaspora*. Besides, in the silvopastoral system and the agrohorticulture system, the spore density in the rhizosphere of predominant grasses varied from 576 to 2032 spores per 100 g soil; the value being greatest in the case of *Hordeum vulgare* (Kumari et al. 2018).

In another important study, Battie-Laclau et al. (2020) observed the respective role of trees and herbaceous vegetation beneath trees in maintaining arbuscular mycorrhizal communities in temperate alley cropping agroforestry systems, and showed that the roots of trees and associated herbaceous vegetation extended several meters within the cropped alley in the topsoil. This study emphasized the role of herbaceous vegetation beneath the trees at maintaining an active arbuscular mycorrhizal network than associated tree roots. Thus, a proper selection of plant species sown under the trees could be useful in maintaining arbuscular mycorrhizal communities.

16.4 Soil Ecosystem Functions and Services

16.4.1 Relationship Between Soil Function, Processes, and Services

The scientific community believes that the definition of soil functions could not be very explicit (Brümmer 1978; Várallyay 1989; Baveye et al. 2016). These authors actually refer soil function as the benefit derived from soil, not only for humans, but also for plants and animals. Soil functions have also been defined as flows arising from natural capital stocks that benefit all living organisms including humans (Baveye 2021). The main ecological functions of soil include nutrient cycling, carbon storage and turnover, water maintenance, soil structure arrangement, regulation of aboveground diversity, biotic regulation, buffering, and the transformation of heavy metals and pesticides (Haygarth and Ritz 2009). The term soil service has been used as a synonym for soil functions and soil processes (Dominati et al. 2014; Keesstra et al. 2012). According to Rodrigues et al. (2021), soil ecosystem services, functions and processes are largely regulated by the properties of soil, and also influenced by various soil degradation processes such as erosion, salinization, loss of soil fertility and compaction, and toxification (FAO 2015). The relationship between soil ecosystem service, function, processes and properties are summarized in Fig. 16.6.

In the past, four major types of ecosystem services have been identified, namely, provisioning services, regulating services, cultural services and supporting services that contribute to human well-being (Daily 1997; MEA 2005). Common International Classification of Ecosystem Services (CICES) developed from the work on environmental accounting undertaken by the European Environment Agency (Haines-Young and Potschin 2017) identified three categories, namely, provisioning services, regulation and maintenance services, and cultural services. For the purpose of this review, we will follow the CICES classification. Ecosystem services provision has been found to occur at multiple scales; for example, carbon sequestration for

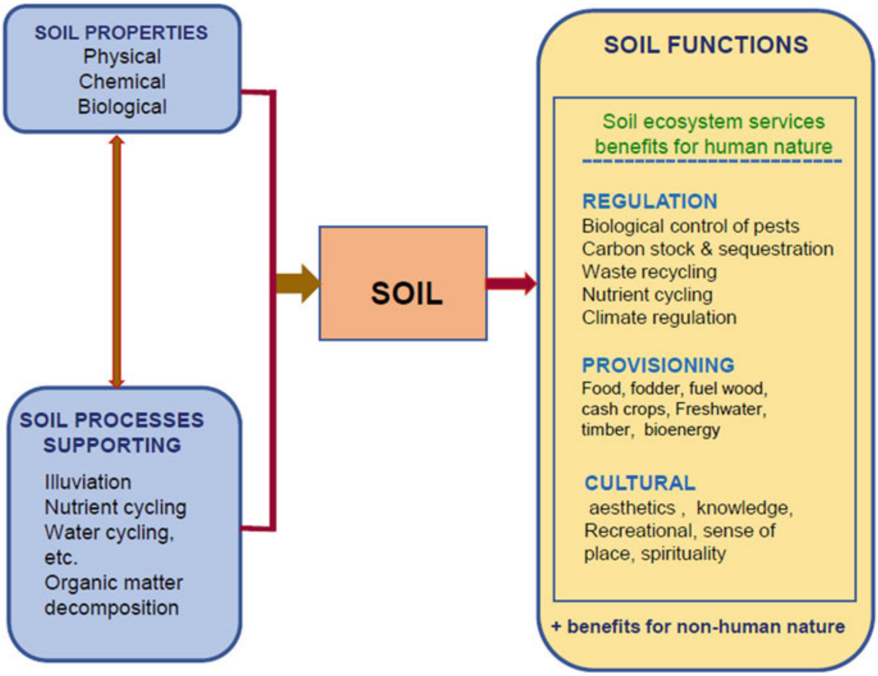

Fig. 16.6 Soil ecosystem services as related to the concepts of soil properties, soil processes, and soil functions. (Source: Rodrigues et al. 2021)

climate regulation at the global scale, and the maintenance of soil structure and fertility at the local scale (MEA 2005). The ecosystem services provided by soils are observed for all three categories (Palmer et al. 2017; Muchane et al. 2020). Some of the authors have emphasized the importance of soil (Dominati et al. 2010), soil biota (Barrios 2007; Brussaard 2012) or more specifically soil invertebrates (Lavelle et al. 2006) in the provision of ecosystem services.

Under provisioning services, soils produce plants, which provide food to humans and animals. While, soils also provide fuel, fibre and genetic materials, and help in bioremediation of polluted areas. Soil biodiversity is essential for the continuous function of the regulating services which include climate regulation, purification of water and flood control, absorption and detoxification of harmful chemicals, controlling diseases and pests, and sequestering greenhouse gases. The regulation of decomposition and nutrients cycling by a high diversity of soil organisms is a key to supporting plant growth and maintaining nutrient balance in soil. Among other categories, supporting services include, soil formation and habitat maintenance (Orgiazzi et al. 2016), nutrient cycling, and primary production. While, the cultural services provided by soils are non-material and non-consumptive, including the benefits which generally affect the psychological state of human beings.

16.4.2 Soil Ecosystem Services in Agroforestry Systems

Agroforestry has been successfully utilized for providing food, fibre and fuel to human beings, while it has also been observed to restore degraded soils (FAO 2005; MEA 2005). Several studies have reported improvement in soil health and soil-based ecosystem services through ecological intensification approaches, leading to increase in the sustainability of agricultural systems (Tomich et al. 2011; Lal 2018; Muchane et al. 2020). During the past couple of decades, several reviews and meta-analysis publications have increased our understanding regarding the beneficial impact of agroforestry on ecosystem services in Africa and Asia, for instance increasing crop yields (Sileshi et al. 2007, 2008; Bayala et al. 2012; Kuyah et al. 2019), controlling diseases and pests (Pumariño et al. 2015), sequestering atmospheric carbon dioxide (Bayala et al. 2018; Chatterjee et al. 2018; Cerda et al. 2019; Ludelling et al. 2011), and increasing infiltration rate and soil moisture content (Kuyah et al. 2019; Muchane et al. 2020). Soils of developing countries in Asia and Africa are generally nutrient poor, associated with several toxicities, and are erosion prone (IUSS 2014). In such scenario, agroforestry systems, which have high potential for improving soil conditions (see: Nair and Garrity 2012; Bayala et al. 2015; Wartenberg et al. 2017) could become a boon for conserving natural resources, and increasing food production, for improving human nutrition and health. Most of the soil ecosystem services fall under the regulation and maintenance services. Here we will briefly describe some important soil-based ecosystem services provided by agroforestry practices.

16.4.2.1 Soil Conservation

The degraded soil lacks important soil properties and functions, which reduces ecosystem services, leading to decline in the productivity of lands (Montgomery 2007; FAO 2015). Increasing soil erosion reduces the size of cultivable land and increases the area of barren land (Lal 1996; Boardman 2006). Soil erosion leads to loss of soil organic carbon (SOC), and fine soil particles important for increasing water holding capacity. Subsequently, due to soil erosion the top soil layer containing nutrient reserves, organic matter and microorganisms is also lost. In central Kenya, Angima et al. (2002) investigated the impact of using tree-grass species combination (contour hedgerow system) for reducing soil erosion, restoring fertility, and improving crop productivity. They found that the contour calliandra (*Calliandra calothyrsus*)–Napier grass (*Pennisetum purpureum*) hedgerows significantly reduced soil erosion, and N and P losses due to runoff in the croplands. Recently, a meta-analysis study by Muchane et al. (2020) suggested that agroforestry practices significantly reduce soil erosion, increase infiltration and micro-aggregation, and lower runoff; there was greater proportion of soil macro-aggregates, and greater stability of soil structure in agroforestry systems, while the effects varied with soil, climate, crop type and tree management practices. Trees in agroforestry act as a physical barrier against soil erosion, and provide litter inputs. Moreover, through root turnover and increased activity of microbes, belowground organic inputs increase in agroforestry systems (Kamau et al. 2017). Recently, Purwaningsih et al. (2020) evaluated the specific vegetation patterns for controlling landslide reactivation on volcanic foot slopes in Java, Indonesia, and observed agroforestry techniques highly effective in controlling erosion processes. They suggested prioritizing trees' and crops' ecological functions for reducing runoff and increasing water absorption in soils.

16.4.2.2 Storage and Cycling of Nutrients

Mixed cropping systems of two or more plant types (i.e. trees, shrubs and herbs) have been reported to increase the storage and cycling of carbon and nitrogen in soils through mutualism and optimum use of soil resources, as compared to the monoculture (Wu et al. 2020). However, the nutrient storage capacity of the agroforestry systems may differ due to diversity of species combinations, and the characteristics of the dominant species (Setälä et al. 2016). According to Barros and Filho (2005), the highly weathered tropical soils exhibit high inorganic phosphorus adsorption capacity and contain low amount of plant available phosphorus. In such circumstances, agroforestry practices have been reported to successfully maintain the organic phosphorus pools in the soil, which also leads to increase in plant available phosphorus (Lehmann et al. 2001; Sileshi et al. 2020b; Zaia et al. 2012).

Another key function of trees has been improvement in soil nutrients availability (Muchane et al. 2020): High organic input through trees in the form of litterfall and fine root production contribute to greater nitrogen and phosphorus availability in the agroforestry systems (Kaur et al. 2000; Lehmann et al. 2001).

In a meta-analysis study, Muchane et al. (2020) showed increases in the availability of soil N and phosphorus (P) to crops, and alleviation of soil acidity across the humid and sub-humid tropics; available soil N increased by 46% and available P by 11%, while soil pH increased by 2% under agroforestry compared to crop monocultures. Thus, agroforestry can be an option for increasing soil nutrient availability to crops; combined use of organic and mineral nutrient inputs to soil, improving nutrient use efficiency through greater synchronization of nutrient release into soil and uptake by crop plants (Muchane et al. 2020).

Trees can also increase soil microbial biomass and nitrogen mineralization. The tree plantations and silvopastoral agroforestry systems raised on sodic soils have a marked effect on the quantity and quality of SOM, which in turn regulates the levels of soil microbial biomass. Kaur et al. (2000) emphasized that the ameliorative effects of the trees and organic matter inputs increase the microbial biomass and their activities, leading to greater nitrogen mineralization in the agroforestry systems. In silvopastoral systems on salt-affected soils, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land use type (Kaur et al. 2000) and tree species (Kaur et al. 2002a).

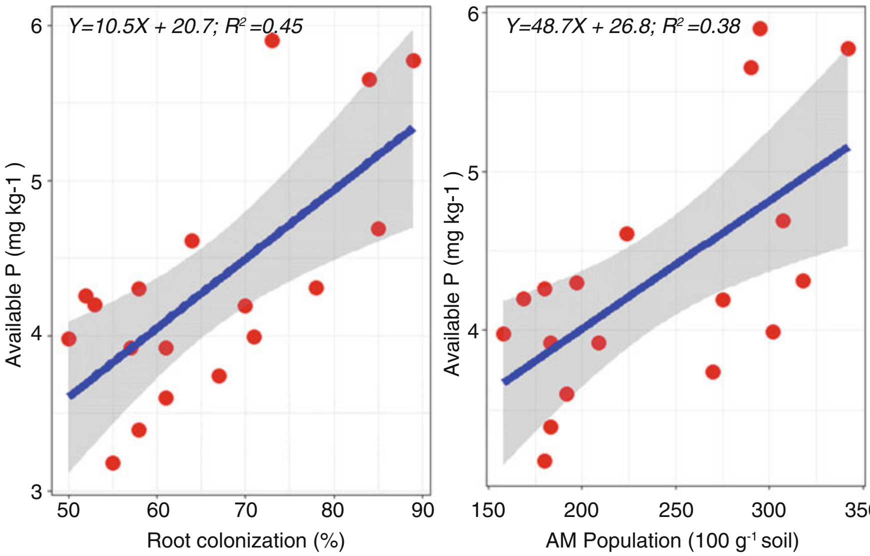

Fig. 16.7 Relationships between the soil phosphorus and per cent AM fungal root colonization and AM spore population in *Prosopis cineraria*-based agroforestry system in Rajasthan, India. (Based on data from Verma et al. 2008)

According to the study by Singh et al. (2013) in energy plantation on highly sodic soil, soil amelioration occurred due to growth of *Jatropha curcas* for 6 years. on sodic soils. The study reported significant increase in soil organic carbon (SOC), nitrogen (N), phosphorus (P), soil microbial biomass (MB-C, MB-N and MB-P), and enzyme activities (dehydrogenase, glucosidase, and protease) beneath the canopy of *Jatropha curcas* than outside the canopy.

Agroforestry practices have also been shown to increase arbuscular mycorrhizal (AM) fungi and nutrient cycling in soils. A good example of this is found in AM associations with *Prosopis cineraria*. This species, locally known as 'Khejri' is a vital component of a traditional agroforestry system in arid zones of India such as Rajasthan. In one study, Verma et al. (2008) assessed arbuscular mycorrhizal (AM) fungi associated with *Prosopis cineraria* from eight districts of Rajasthan, India. These workers reported 37 species of AM fungi belonging to *Acaulospora, Gigaspora, Entrophospora, Scutellospora,* and *Sclerocystis* in the rhizosphere soil of *Prosopis cineraria.* Their study showed a significant relationship of tree rhizosphere soil P with AM spore population and per cent AM fungal root colonization (Verma et al. 2008, Fig. 16.7).

In a study by Pande and Tarafdar (2004), for neem (*Azadirachta indica*)-based agroforestry systems in Rajasthan, the AM spore density was higher in the tree and crop rhizosphere soils as compared to that of the uncropped sites. Moreover, AM fungal root colonization was higher in tree roots than crop roots. The factors like Fe, Zn and maximum temperatures affected the AM fungal populations significantly in the neem rhizosphere. In soils of the associated crop rhizospheres, electrical conductivity (EC), organic C, Fe, P, $CaCO_3$, maximum temperature, rainfall and humidity affected the AM populations.

16.4.2.3 Improved Soil Biological Quality

The biological qualities of soil are related to soil biological activity, which is a function of the abundance and diversity of organisms such as earthworms, termites, ants, fungi, bacteria, etc. (Mafongoya and Sileshi 2020). Earthworms contribute to ecosystem services through pedogenesis, development of soil structure, water regulation, nutrient cycling, primary production, climate regulation, pollution remediation and cultural services (Blouin et al. 2013). Ants, termites, and earthworms modify their surrounding environment, and thus affect soil water and nutrient dynamics through their impact on other soil organisms (Lavelle et al. 1997). In tropical and temperate areas, earthworms, ants and termites are the main promoters of carbon stabilization by creating biogenic structures (casts, galleries, nests and mounds) that form organo-mineral associations (Vidal et al. 2016). Soil structure formed by plant roots, earthworms, macro-arthropods, and fungi is essential habitat for other soil organisms and provide a long-term support for aboveground communities (Lavelle et al. 2016).

The diversification of plant species in agroforestry systems generates diverse microhabitats which provide habitats to a wide range of biological species (Laossi et al. 2008; Roy et al. 2017). In the Central Indian semi-arid regions, even at the early establishment phase, the silvopastoral systems and the intensive agricultural systems have exhibited similar soil biological diversity as found in the natural systems (Bano 2006). Moreover, the microarthropod diversity has been found to increase in the degraded Central Indian grasslands due to development of silvopastoral systems (Roy et al. 2017), which also led to the increase in the productivity of the region (Roy et al. 2008). In the north-western highlands of Rwanda, Africa, Yamaoh et al. (1986) evaluated the effects of pruning of the three leguminous shrubs on soil properties at 0–15 cm soil depth, and reported 46% greater soil MB-C under hedgerow intercropping with *Gliricidia* and *Senna* sp., compared to the monoculture. In south-western Nigeria, Kang et al. (1990) and Hauser (1993) found higher activity of earthworms under hedgerow intercropping, compared to monocultures. Hauser (1993) also reported greater worm casts under Leucaena hedgerow (117 Mg ha^{-1}), compared to the no tree control plots of *Zea mays* (28 Mg ha^{-1}).

According to Rao et al. (1998), the rate and extent to which biophysical resources are captured and utilized by the components of an agroforestry system are determined by the nature and intensity of interactions between the components. For instance, besides the advantages of termites for creating heterogeneous environment, these soil inhabiting species could also show negative impact on agro-ecosystems (Jouquet et al. 2018). In such circumstances, agroforestry practices have also been observed to exhibit capacity of controlling termite populations. Studies in Asia and Africa have reported reduction in crop damage by termites by inter-cropping with legumes, mulching, or by keeping tree leaf litter (Sands 1977; Shivashankar et al.

1991; Sekamatte et al. 2003; Girma et al. 2009; Kihara et al. 2015). This attracts ants feeding on termites, e.g., *Leptogenys processionalis* in India (Rajagopal and Ali 1984); or *Pheidole megacephala* and *Megaponera foetens* in Africa (Lepage 1981), or otherwise crops get protected by termites by the fact that termites prefer more palatable mulch and litter as a food source, compared to crops and trees (Mugerwa 2015a, b).

16.4.2.4 Soil Carbon Sequestration

Several case studies both in Asia and Sub-Saharan Africa have indicated that agroforestry systems can sequester greater amounts of above- and belowground C compared to conventional agricultural systems (Kaur et al. 2002a; Kaonga and Bailey-Smith 2009; Gupta et al. 2009; Saha et al. 2009; Sileshi et al. 2007; Takimoto et al. 2009; Gaur and Gupta 2012). In a meta-analysis for Sub-Saharan region, Bayala et al. (2018) showed increase in both SOC and soil N content of four agroforestry practices, i.e., alley cropping, improved fallow, mulching and parkland, as compared to corresponding treeless control plots. According to their study, the percentage increase in SOC for alley cropping, improved fallow, mulching and parkland were 20.6%, 22.8%, 39.5%, and 35.5%, respectively, while the percentage increase in N content of soil for the four agroforestry practices were 32.1%, 15.3%, 32.4%, 35.5%, respectively. A recent analysis of SOC stocks in agroforestry systems across India (Nath et al. 2021) showed higher SOC stocks in agrosilvopastoral (53.0 Mg C ha^{-1}) than in agrisilvicultural (44.1 Mg C ha^{-1}) and silvopastoral systems (33.5 Mg C ha^{-1}).

Studies in different agroforestry systems and grassland systems of salt-affected soils, have reported soil carbon sequestration potential in 0–30 cm soil layer, which ranged from 6.839 to 20.50 Mg ha^{-1} $year^{-1}$ (Dagar and Gupta 2020). In the case of *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* agrisilvopastoral systems on sodic soils at Bichhian, north-west India, the soil carbon pool was: 13.431 Mg C ha^{-1}, *Prosopis juliflora* + *Desmostachya bipinnata* ; 9.621 Mg C ha^{-1}, *Prosopis juliflora* + *Sporobolus marginatus* (Kaur et al. 2002a). Studies on semiarid hyperthermic camborthids regions of North-West India, Kumari et al. (2018) reported greater SOC in the case of silvopastoral systems as compared to the native grassland system Moreover, the integration of trees with forage grasses improved SOC significantly on calcareous soils irrigated with saline water.

Soil structure regulates to a large extent many physical, chemical, and biological properties of soils. An aggregate is a naturally occurring group of soil particles, which helps in the movement of air and water through the soil and protect the SOM (Oades 1984). Consequently, the soil physical fractionation forms a useful tool to evaluate changes in soil carbon and SOM dynamics. The microaggregates (250–53 μm), and silt and clay fraction (<53 μm) form a large fraction of the soil aggregates and protect most of the SOC in sodic soils. In the study of Kumari et al. (2018), the silvopastoral agroforestry systems of *Acacia nilotica* and *Salvadora*

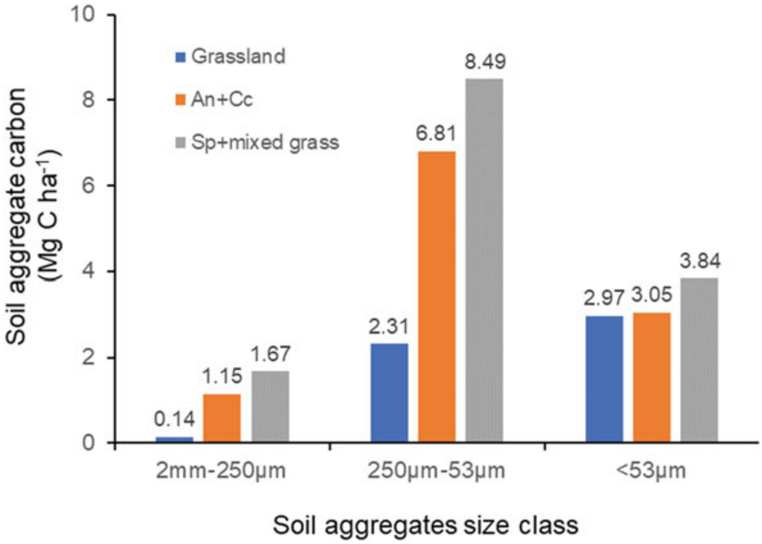

Fig. 16.8 Soil aggregate carbon stock in 30 cm soil depth in native grassland and silvopastoral systems of An + Cc = *Acacia nilotica* + *Cenchrus ciliaris*; and Sp+mix-grass = *Salvadora persica* + mixed grasses on calcareous soils at Hisar, north-western India. (Based on Kumari et al. 2018)

persica along with the native grasses of *Cenchrus ciliaris* and *Panicum miliare,* and agrohorticulture system of *Carissa carandas*, with *Hordeum vulgare* effectively improved the soil structure and strengthened the stability of water-stable soil aggregates. This study showed that different agroforestry systems improved the SOC content and storage in aggregates of different sizes as compared to that of native grassland site (Fig. 16.8). Moreover, the long-term adoption of agroforestry interventions significantly increased the content of water-stable macro-aggregates, and the microaggregates ranging from 250 to 53 μm, which were also the main sites of SOC storage. Besides, the tree-based systems had a greater effect on macro- and micro-aggregates in surface soil layer as compared to other depths, suggesting an aggregate stratification phenomenon (Kumari et al. 2018).

16.5 Litter Decomposition and Nutrient Release Patterns

Decomposition is a complex and multi-step process of breaking down of complex organic matter by soil organisms to release free the nutrients for renewed uptake by the plants (Swift et al. 1979). The general relationship between rates of decomposition, resource quality, environmental factors and decomposers organisms have been reviewed widely (see Singh and Gupta 1977; Swift et al. 1979; Heal et al. 1997; Zhang et al. 2008). The decomposition of litter in agroforestry systems differs from that of natural forests and agricultural system, because of differences in the types and quality of organic residue inputs (Mafongoya et al. 1998). Agroforestry systems contain a mixture of plant species such as trees and crops that have different growth forms and residue qualities, the residues of mixed quality decompose simultaneously within the same soil matrix and may differ in their pattern of decomposition (Zeng et al. 2010). Litter decomposition is explained by various drivers, including plant functional traits, climate, chemical composition of litter, and the activity and composition of decomposing biota (Swift et al. 1979). The litter decomposition rates, resource quality of litter and nutrient release patterns from decomposing litter in agroforestry systems are briefly described as follows.

16.5.1 Litter Decomposition Rates

Litter decomposition rates in tropical agroforestry systems in Asia have been reported in number of studies (Lekha and Gupta 1989; Das and Das 2010; Nath and Das 2011; Hossain et al. 2011; Hasanuzzaman and Hossain 2014; Saini and Gupta 2017; Gaur 2013). In some recent studies, leaf litter decomposition rates in agroforestry systems of Africa have been studied in relation to resource quality of litter, decomposer organisms and the environmental conditions (Teklay and Malmer 2004; Gnankambary et al. 2008; Mahari 2014; Munthali et al. 2015; Akinyele and Donald-Amaeshi 2021; Negash and Starr 2021; Asigbaase et al. 2021).

The litter bag technique has been found to be useful for studying litter decomposition rates in different types of ecosystems because of easy applicability and low cost (Singh and Gupta 1977). Most of the litter decomposition studies (using the litter bag technique) in agroforestry systems have used a single exponential mathematical model (Jenny et al. 1949; Olson 1963) for describing the pattern of decomposition, and the form of the equation used is

$$\ln\left(x_t/x_o\right) = -kt$$

where x_t and x_o are mass remaining at time t and time t_o, respectively; k is the decomposition rates constants (day^{-1}/week^{-1}/ or year^{-1}). The half-life is the time required for 50% of leaf litter to decompose, it can be computed as: $t_{50} = 0.693/k$ (Olson 1963). For comparing different studies in agroforestry systems, decomposition rate constants have been expressed on per year basis (Table 16.4).

The double exponential model is based on the assumption that the litter has two main substrate quality components, and has been used in only a few studies in the agroforestry systems (Teklay and Malmer 2004). The idea is that there is a change in litter quality of plant residues with the progress of decomposition (Berg and Staaf 1980; Lousier and Parkinson 1976). Assuming that residue decomposition occurs in two distinct phases, the double exponential model (Weider and Lang 1982) takes the following form:

Table 16.4 Decomposition rate constant (k year^{-1}) for various litter species in agroforestry systems of Asia and Africa based on some recent studies

AF practice/location	Litter species/type	Decomposition rate constant (k year^{-1})	Reference
Agroforestry systems of Asia			
Home garden Kerala, India.	Leaf litter of six multipurpose tree species	2.04–4.06	Isaac and Nair (2006)
Home garden Barak Valley, Assam	10 tree species Leaf litter, sheath litter	1.34–6.17	Das and Das (2010)
Home garden, Assam, north-east India	*Bambusa cacharensis*/Leaf (Sheath litter)	1.44; 1.31	Nath and Das (2011)
Home garden, Assam, north-east India	*Bambusa vulgaris*/ Leaf litter, (Sheath litter)	1.71; 1.21	Nath and Das (2011)
Home garden, Assam, north-east India	*Bambusa balcooa*/Leaf (Sheath litter)	1.64; 1.07	Nath and Das (2011)
Traditional agroforestry systems in (Assam) and (Arunachal Pradesh) north-east India	Leaf litter of 12 agroforestry species	0.22–8.61	Tangjang et al. (2015)
Agrisilviculture Agroforestry *Populus deltoides* + wheat *Populus deltoides* + sugarcane, Northern India	*Populus* leaf, *Populus* leaf + wheat straw; Populus leaf + sugarcane straw	4.53; 3.76; 1.79	Saini and Gupta (2017)
Mixed plantations of tree species, Khulna University campus, Bangladesh	leaf litter of *Melia azedarach; Azadirachta indica; Dalbergia sissoo*	6.67; 5.12; 3.91	Hossain et al. (2011)
Paddy field of Khulna district in south-western Bangladesh, dry and wet seasons	Agroforest horticultural tree species	0.88–2.34	Hasanuzzaman and Hossain (2014)
Sumberjaya benchmark area, West Lampung, Indonesia	Composite litter from monoculture, shaded and multistrata coffee systems and natural forest	0.37–0.54	Hairiah et al. (2006)
Agroforestry systems of Africa			
Shaded-coffee, Wondo Genet, Ethiopia	Leaf litter *Cordia africana*	1.20	Teklay and Malmer (2004)
Shaded-coffee, Wondo Genet, Ethiopia	Leaf litter *Albizia gummifera*	1.77	Teklay and Malmer (2004)
Indigenous agroforestry Boni village, Burkina Faso, west Africa	leaf litters of *Faidherbia albida*, mixed litter, with fertilization	5.16–8.92	Gnankambary et al. (2008)
indigenous agroforestry Boni village, Burkina Faso, west Africa	leaf litters of *Vitellaria paradoxa,* mixed litter, with fertilization	1.04–2.92	Gnankambary et al. (2008)
low-input Sahelian cropping system fallow field, Sadore´, Niger	Millet straw; *Acacia tumida* prunings	2.19–2.45	Ibrahim et al. (2018)

(continued)

Table 16.4 (continued)

AF practice/location	Litter species/type	Decomposition rate constant (k year^{-1})	Reference
Indigenous agroforestry farms, south-eastern Ethiopia	Leaf litter of six tree species	2.582–6.108	Negash and Starr (2021)
Cocoa agroforestry systems, Ghana	cocoa and shade tree leaf litter, organic and conventional cocoa	1.93–1.4	Asigbaase et al. (2021)
Agroforestry trees species Akinyele Local Government Area, Oyo State, Nigeria	leaf litter of *Cola nitida*, *Annona muricata* and *Senna siamea*	0.73–1.825	Akinyele and Donald-Amaeshi (2021)

$$M_t = Ae^{-k_1 t} + Be^{-k_2 t};$$

where M is the mass (dry weight) or nutrient remaining, t is time, and k_1 and k_2 are rate constants for fast and slow decomposing fractions, A and B are the amount of each fraction initially.

In agroforestry systems of the Asian and African regions, the decomposition rate constants are found to be highly variables and often related to litter quality and climatic conditions (Table 16.4). Litter decomposition studies in the home gardens of southern Kerala in India showed that the decay rate coefficients varied significantly among the species; *Artocarpus heterophyllus* and *Anacardium occidentale* to be the most labile litter species and *Swietenia macrophylla* be the most recalcitrant (Isaac and Nair 2006). In traditional home gardens of Barak Valley, Assam, north-east India, litter decomposition rates of ten multipurpose trees showed that the decay rate (k year^{-1}) was highest for *Sapium baccatum* ($k = 6.17$ year^{-1}) and the lowest for *Bambusa cacharensis* ($k = 1.34$ year^{-1}); *Sapium baccatum* and *Toona ciliata* were found to be the most labile litter species (Das and Das 2010).

In the case of leaf and sheath litter of *Bambusa cacharensis*, *B. vulgaris* and *B. balcooa* in a home garden of Dargakona in Assam, in northeast India, litter mass expressed as a percentage of the original dry mass, decreased exponentially over time (Nath and Das 2011). In this study, the decomposition rate constants over the study period was greatest for *B. vulgaris* ($k = 1.71$ year^{-1}) and lowest for *B. cacharensis* ($k = 1.44$ year^{-1}) (Table 16.4). The leaf and sheath litter having higher N and lower C/N ratio showed high decomposition rate compared to that of litters with lower N and higher C/N Ratio (Nath and Das 2011).

In monoculture, shaded and multistrata coffee systems and natural forest in West Lampung, Indonesia, the decomposition rate of standing litter were found to be very slow (Hairiah et al. 2006). During the 16 weeks of the litterbag decomposition study, only 30–40% of the dry weight was lost from the bags, either through the process of decomposition and/or transfer of litter to the soil. The rate of decomposition varied from 0.37 to 0.54 year^{-1}, with a mean residence time for the litter in the range of 2–3 years (Hairiah et al. 2006) (Table 16.4).

Table 16.5 Average decay constant and half-life (t^{50}) of leaf litter of selected cropland agroforest horticultural tree species of Khulna district in south-western Bangladesh (Hasanuzzaman and Hossain 2014)

Litter species	Dry season average decay constant (k year^{-1})	Dry season t^{50} (Days)	Wet season average decay constant (k year^{-1})	Wet season t^{50} (Days)
Artocarpus heterophyllus	2.14	118	2.34	108
Ziziphus jujuba	2.03	125	2.24	113
Mangifera indica	1.44	176	1.61	157
Litchi chinensis	0.88	289	0.94	270

For three agroforestry species in Bangladesh, Hossain et al. (2011) found that the rate of decomposition of *Melia azedarach* leaf litter was higher, whereas the leaf litter of *Dalbergia sissoo* showed a lower rate of decomposition. The decay constant (k) was comparatively higher for *M. azedarach* (k = 6.67 year^{-1}), followed by *Azadirachta indica* (k = 5.12 year^{-1}) and *D. sissoo* (k = 3.91 year^{-1}). Moreover, the rate of leaf litter decomposition of each species showed a significant ($p < 0.05$) positive relationship with monthly rainfall (r = 0.86–0.88) and temperature (r = 0.71–0.81).

Hasanuzzaman and Hossain (2014) analysed leaf litter decomposition and nutrient dynamics of *Mangifera indica*, *Ziziphus jujuba*, *Litchi chinensis*, and *Artocarpus heterophyllus* in cropland agroforest horticultural tree species of Bangladesh, where the decomposition rate constant was the highest for *A. heterophyllus* (k = 2.14–2.34-year^{-1}) and the lowest for *L. chinensis* (k = 0.88–0.94 year^{-1}). For all the four litter types, there was a significantly ($p < 0.05$) higher decay constant, and faster nutrient return during the wet season (Table 16.5).

In the *Populus deltoides* agroforestry system at Kurukshetra, northern India, litter decomposition rate constants ranged from 3.76 to 1.79 year^{-1} (Saini and Gupta 2017) for *Populus* leaf litter, *Populus* leaf litter + wheat straw and *Populus* leaf litter + sugarcane straw (Table 16.4). In this study, an initial rapid rate of decomposition of *Populus* leaves in the months of December to March was found to coincide with the growth period of wheat crop in the system.

In the agrisilviculture agroforestry system of *Eucalyptus tereticornis* with sugarcane and wheat in north western India, the decomposition rates were affected by the litter type, being greater for *Eucalyptus* leaf litter (Fig. 16.9) as compared to that of the wheat straw (Gaur 2013; Gupta et al. 2019). The decomposition rate constants for *Eucalyptus* leaf litter, wheat straw and sugarcane, *Eucalyptus* leaf litter + wheat straw, and *Eucalyptus* leaf litter + sugarcane straw ranged from 1.13 to 2.15 year^{-1} (Gaur 2013; Gupta et al. 2019), and the half-life period was 117–224 days. This study suggested that mixing *Eucalyptus* leaf litter with wheat straw or sugarcane straw seems to be a promising option to regulate decomposition/mineralization rates in accordance with the requirement of crops in the agroforestry system.

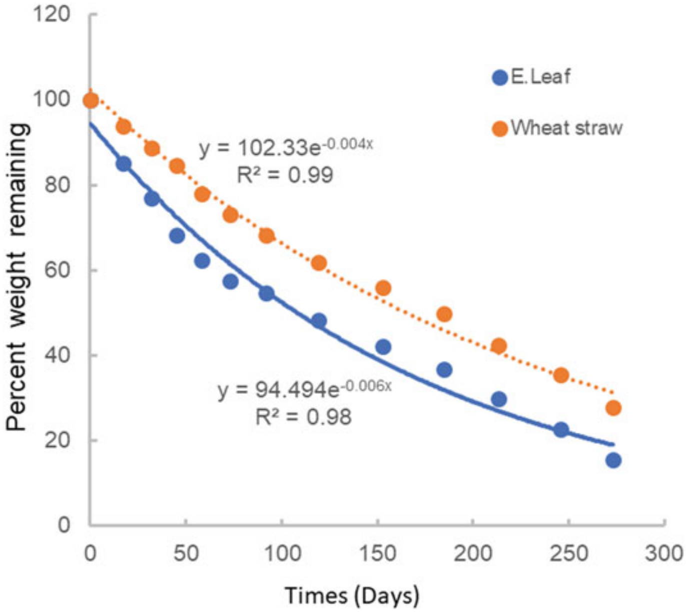

Fig. 16.9 Per cent weight remaining of *Eucalyptus* leaf, wheat straw, under *Eucalyptus tereticornis* agroforestry system on a moderately alkali soil at Salimpur, Kurukshetra, Northern India. (Based on Gaur 2013)

Teklay and Malmer (2004) studied decomposition of the leaf litter of *Cordia africana* and *Albizia gummifera* under shaded-coffee and agricultural land-uses at Wondo Genet in southern Ethiopia. In this study, the mass loss of *Albizia* was faster as compared to that of *Cordia*, but there was no significant land use effect on the decomposition rates. Mass loss for the two species for this study was explained by the double exponential decay model (Lousier and Parkinson 1976). However, the quadratic model provided the best fit for explaining the pattern of decomposition (Teklay and Malmer 2004).

Gnankambary et al. (2008) showed that *Faidherbia albida* leaf litter decomposed faster ($k = 0.060–0.171$ week^{-1}) than *Vitellaria paradoxa* litter ($k = 0.020–0.056$-week^{-1}). Whereas mixing litters accelerated the decomposition rate of both *F. albida* and *V. paradoxa* litter. Thus, mixing litters of contrasting qualities may be a promising option for regulating decomposition/mineralization rates from organic material in the agroforestry system; buried litter decomposed more rapidly than surface litter (Gnankambary et al. 2008). Furthermore, applications of inorganic N and readily available P (TSP) increased the litter decomposition rate, and the presence of high litter quality increased the decomposition rate of low-quality litter.

In low-input Sahelian cropping system, the decomposition rates of millet straw and *Acacia tumida* prunings were moderately high and the *k* values ranged from 2.19 to 2.45 year^{-1} (Ibrahim et al. 2018). For conventional cocoa agroforestry systems in Ghana, the mean monthly mass loss of litter was higher on organic farms

(9.2–14.4 g month^{-1}) as compared to conventional farms (4.2–7.3 g month^{-1}) in the first 5 months (Asigbaase et al. 2021). Subsequently, the annual rate of decomposition (k) was also higher on organic farms ($k = 1.93$ year^{-1}) compared to that of the conventional systems ($k = 1.4$ year^{-1}) (Asigbaase et al. 2021) (Table 16.4). In this study, the estimated k values for both litter decomposition and nutrient mineralization correlated with soil pH and moisture content, but not initial litter chemistry.

Negash and Starr (2021) studied decomposition rates of six species including *Cordia africana*, *Croton macrostachyus*, *Erythrina brucei*, *Mangifera indica, Millettia ferruginea,* and *Persea americana* in the indigenous agroforestry systems practiced by smallholders in south-eastern Ethiopia. According to this study, the decay rate constant (k) values for the six leaf litter species varied from 2.582 to 6.108 year^{-1}, and half-life was 41–112 days. Moreover, depending on species, estimated carbon losses from litterfall was found to be 18–58% lower than the annual litterfall carbon inputs in the agroforestry systems. Thus, litterfall was sufficient to maintain soil organic carbon contents and the soil fertility of these unique agroforestry systems (Negash and Starr 2021).

Munthali et al. (2015) studied the decomposition patterns of different residues of *Tephrosia vogelii* and *Tephrosia candida,* leguminous species widely used in improved fallows in Malawi. The decomposition pattern was biphasic with an initial rapid phase followed by a slower phase. The decomposition of residues of the two species followed the same pattern and order; the highest being in the mixture of leaves + twigs + stover and lowest in maize stover alone. The *Tephrosia* fallow biomass alone decomposed considerably faster attaining their half-life within 2–3 weeks and over 95% within 8–25 weeks, but when mixed with maize stover, decomposition was slowed down. The decomposition rate constants (k) ranged from 0.15 week^{-1} for maize stover alone to 0.34 week^{-1} with mixture of *T. candida* leaves + twigs + maize stover. The N release for both species rate (kN) ranged between 0.12 and 0.39 week^{-1}. Although twigs had almost released 50% of N within 2 weeks (Munthali et al. 2015). These results indicate that *T. candida* and *T. vogelii* produce high quality litter, which can be used for short-term correction of soil fertility. However, the accelerated decomposition and nutrient release means that it has limited potential for long-term build-up of soil fertility. Therefore, for long-term build-up of soil organic matter, *Tephrosia* residues may be mixed with maize stover to slow down decomposition.

16.5.2 Litter Quality and Nutrient Release Pattern

Litter quality refers to the intrinsic characteristics of litter that influence its utilization by heterotrophs and mineralization by decomposer organisms. The physical, chemical and inhibitory components of litter regulate decomposition rates in different types of ecosystems (Swift et al. 1979; Cadish and Giller 1997). Consequently, the initial lignin concentration or the lignin/nitrogen ratio has proved to be an effective index of decomposition rates and nitrogen release from the litter (Melillo et al.

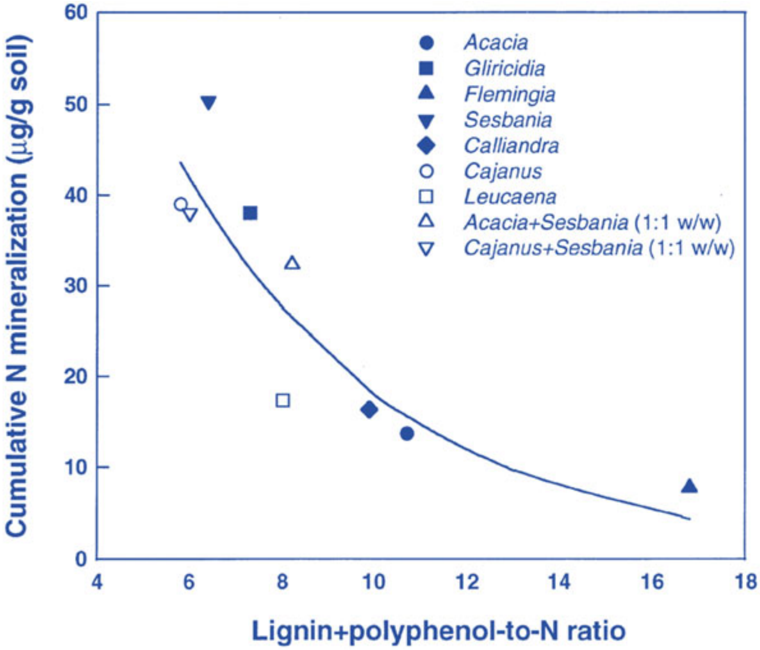

Fig. 16.10 The relationship between cumulative mineralized N and the (lignin + polyphenol):N ratio of leaves of multipurpose trees. (Adapted from Mafongoya et al. 1997)

1982). Litter chemical quality is most often described as the N or lignin concentration, the C:N ratio or the lignin:N ratio, and therefore, these parameters are also frequently measured (Aerts 1997; Campbell et al. 2016). A comprehensive study with data from 110 research sites, globally distributed, showed that the total amount of nutrients (N, P, K, Ca and Mg combined) and the C:N ratio accounted for 70.2% of the variability measured in litter decomposition (Zhang et al. 2008).

The residues of high quality (high in nutrients and low in lignin) decompose rapidly, whereas the residues of low quality (high in lignin and polyphenols) decompose slowly. It has been reported that some polyphenols such as condensed tannins could inhibit exozyme activity and have been found to reduce decomposition rates (Palm and Sanchez 1991; Tian et al. 1995). In some agroforestry systems, the (PP + L):N ratio was found to be a good index to predict mass loss and N release pattern (Mafongoya et al. 1997, 1998) (Fig. 16.10).

Organic materials with a low C/N ratio (<25) and low lignin (<15%) and polyphenolics (<3%) (Palm and Sanchez 1991) are considered to be of high-quality, and generally exhibit high rates of decomposition and rapid nutrient release. Due to their high N content, litter from leguminous trees mostly decompose rapidly (e.g. *Gliricidia sepium* and *Leucaena leucocephala*) (Handayanto et al. 1994). However, leguminous trees with high polyphenol ('tannin') content such as *Peltophorum dassyrachis, Calliandra calothyrsus* and *Erythrina orientalis* decompose slowly over periods of 16 weeks (Handayanto et al. 1994). Leaf litter of most nonlegume trees grown for timber and/or fruit has a high lignin concentration (>20%), and are expected to decompose slower than the leguminous trees. In agroforestry systems, tree species with high quality of litter appear desirable as the release of nitrogen and other nutrients would be synchronized with the plant uptake requirements (Young 1989). In some agroforestry systems, small and fast-growing leaf litter species such as *Leaucena, Gliricidia, Flemingia* and *Cassia* have been successfully combined with maize for faster litter decomposition (Wilson et al. 1986; Yamaoh et al. 1986). The litter quality parameters in some agroforestry systems are compiled in Table 16.6.

According to Isaac and Nair (2006), the leaf decomposition rates were related to the initial lignin content of the litter. Polyphenol + lignin:N ratio revealed its significant influence on the decomposition constant. In this study, the release of nitrogen, phosphorus and potassium from the decomposing litter was almost complete during the study period in all species in spite of the initial phases of accumulation observed for nitrogen and phosphorus. The study suggested that the temporary immobilization of nitrogen and phosphorus leads to slow release of the nutrients from the decomposing litter, which may help minimize the nutrient losses from the system, helping to synchronize nutrient uptake requirements of the annual crops in the home garden (Isaac and Nair 2006). The macronutrients in this study were released in the order K>N/P. The higher rates of decay and nutrient turnover in *M. indica*, A. *heterophyllus* and *A. occidentale* foliage indicated the potential of using these species for nutrient inputs in home gardens as well as agriculture (Isaac and Nair 2006).

In the study of Das and Das (2010) in traditional home gardens of Barak Valley, Assam, northeast India, the C/N ratio of litter varied significantly among the species. The authors found a significant positive correlation ($p < 0.05$) between decomposition rate (k) and initial nitrogen concentration of litter ($r = 0.52$, Fig. 16.11a), while a negative correlation was found for C/N ratio ($r = -0.41$) (Fig. 16.11b). The litter species in the home gardens showed different nitrogen release patterns; some species showed continuous release of N from the decomposing litter while other species exhibited an initial release followed by net accumulation of nitrogen. The study observed higher decomposition rate and rapid mineralization of N for *S. baccatum*. The leaf litter of *B. cacharensis* was slow to decompose and accumulated to form a thick litter layer in the bamboo groves. Thus, multiple tree species in traditional home gardens produce a combination of low quality and high quality litter with variable nutrient release pattern facilitating the differing rate of nutrient uptake by the plants in home gardens (Das and Das 2010).

The dependence of litter decomposition on N contents, at least during the early stages, is widely known (Berg and Laskowski 2006). For the indigenous agroforestry systems practiced by smallholders in south-eastern Ethiopia, Negash and Starr (2021) showed a significant correlation between k and initial litter N content, and the nearly significant correlation between k and C/N ratio. In this study, the partial least squares regression analysis revealed that litter N contents played a significant role in regulating decomposition rates. Furthermore, it was interesting to note that the

Table 16.6 Initial chemical composition of the leaf litter of some agroforestry systems

Species/ combination	Country	Nitrogen (%)	Carbon (%)	Lignin (%)	Pp (%)	References
Bamboo species leaf	Home garden, Assam, north-east India	0.82–0.98	34.6–37.5	nd	nd	Nath and Das (2011)
Bamboo species sheath	Home garden, Assam, north-east India	0.63–0.71	42.0–46.1	nd	nd	Nath and Das (2011)
Leaf litter, 10 tree species	Home gardens Barak Valley Assam, India	0.77–2.16		nd	nd	Das and Das (2010)
Populus leaf, Wheat straw, Sugarcane straw	Agrisilviculture Agroforestry Northern India	1.93, 0.61, 0.64	40.46, 39.04, 41.3	11.12, 12.14, 15.54	nd	Saini and Gupta (2017)
Tree species Leaf litter	Southwestern Bangladesh	0.90–2.18	nd	nd	nd	Hasanuzzaman and Hossain (2014)
Remnant forest Sun and shade coffee	West Lampung, Indonesia	1.24–2.20	nd	21.1–37.7	4.25–6.37	Hairiah et al. (2006)
Leaf litter *Cordia africana*	Ethiopia	3.75	nd	26.4	4.6	Teklay and Malmer (2004)
Leaf litter *Albizia gummifera*	Ethiopia	2.54	nd	30.3	2.9	Teklay and Malmer (2004)
Faidherbia albida, mixed litter	Burkina Faso, west Africa	1.81	49.4	nd	nd	Gnankambary et al. (2008)
Vitellaria paradoxa, mixed litter	Burkina Faso, west Africa	0.84	53.4	nd	nd	Gnankambary et al. (2008)
Millet straw	Niger	1.69–0.84	nd	7.73	0.63	Ibrahim et al. (2018)
Acacia tumida prunings	Niger	2.0–2.26	nd	21.95	1.26	Ibrahim et al. (2018)
Leaf litter of six tree species	South-eastern Ethiopia	1.40–2.98	46.0–50.4	nd	nd	Negash and Starr (2021)
Tephrosia candida leaves	Central Malawi	5.18	36.4	nd	nd	Munthali et al. (2015)
Tephrosia candida twigs	Central Malawi	2.95	35.6	nd	nd	
Tephrosia vogelii leaves	Central Malawi	5.02	32.1	nd	nd	
Tephrosia vogelii twigs	Central Malawi	2.75	31.7	nd	nd	

Pp Polyphenol, nd not determined

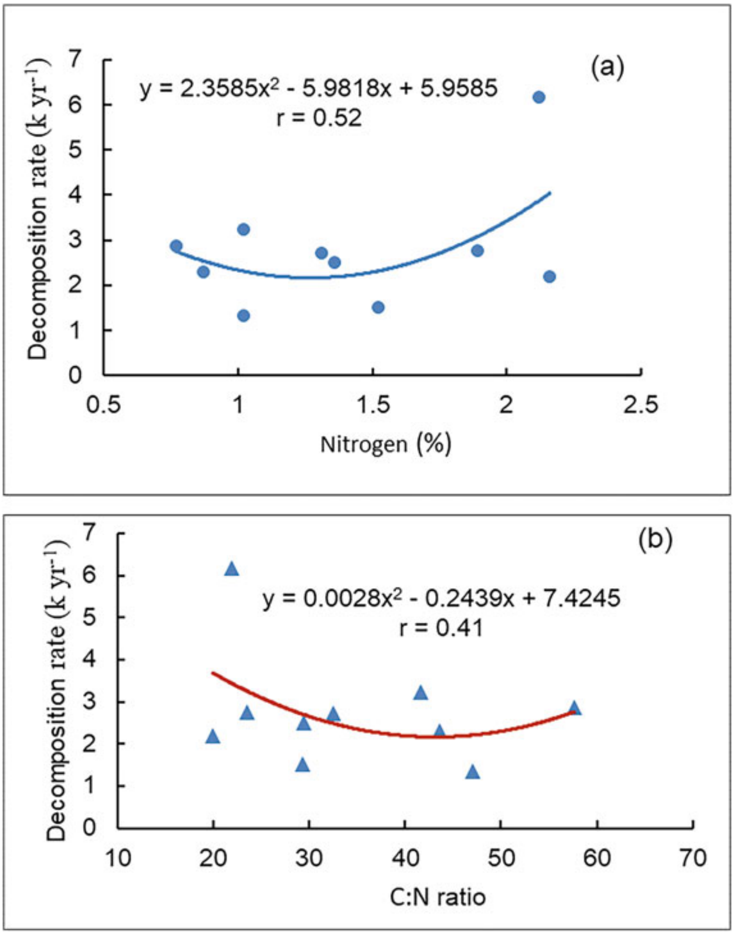

Fig. 16.11 The relationship between the litter decomposition rate and nitrogen concentration (**a**), and the C:N ratio (**b**) in the traditional home gardens of Barak Valley, Assam, northeast India. (Based on data from Das and Das 2010)

highest *k* values (*E. brucei,* 3.775–4.881 year^{-1}; *M. ferruginea,* 3.315–6.108 year^{-1}) were associated with nitrogen fixing trees (Negash and Starr 2021).

The standing litter used in the decomposition experiment by Hairiah et al. (2006) were of 'low quality'. In their study, the quality of standing litter in the remnant forest and sun coffee were still of poorer quality than in the multistrata and shaded coffee systems (Hairiah et al. 2006). The ratio of (lignin + polyphenol) to N ranged from 22 to 17 in different systems. According to VanLauwe et al. (1997), a (lignin + polyphenol) to N ratio >10 is considered as 'low quality'. Leaf litter of *Mangifera indica*, *Zizyphus jujuba*, *Litchi chinensis*, and *Artocarpus heterophyllus* showed a similar pattern (K > N > P) of nutrient release from decomposing litter

(Hasanuzzaman and Hossain 2014). However, *Zizyphus jujuba* showed comparatively higher return of N, P, and K as compared to that of other species.

Saini and Gupta (2017) showed variations in nitrogen release patterns from decomposing *Populus* leaf litter; wheat straw and sugarcane straw in the agrisilviculture agroforestry system in northern India. In this study, there was increase in N concentration of decomposing wheat straw up to 160 days, and a release phase at the end of decomposition. In leaf litter of *Populus* and sugarcane straw, the increase in N concentration was conspicuous after 64 days, followed by release of nitrogen. The single exponential model showed a good fit for the temporal variation in per cent nitrogen remaining over a period of time of 190 days (Fig. 16.12). The half-life for the release of nitrogen was 114, 55 and 141 days for wheat straw, *Populus* leaf litter and sugarcane straw, respectively.

Teklay and Malmer (2004) explored mineralization of macronutrients and loss of organics from leaves of *Cordia africana* and *Albizia gummifera* under shaded-coffee and agricultural land-uses during the dry season. In this study, *Cordia* had higher content of ash, K, P, cellulose, lignin and a higher C-to-N ratio while *Albizia* had higher contents of N, polyphenol, condensed tannins and a higher C-to-P ratio. These workers stated that under drier conditions, the organic residues with high content of polyphenols, particularly condensed tannins, and could decompose faster than those with lower content indicating that indigenous tree species of 'poor quality' might be quite useful as an organic input for improving soil fertility and productivity in the tropics (Teklay and Malmer 2004). The study emphasized that there was initial N immobilization in decomposing leaf litter of *Cordia africana* and *Albizia gummifera* under shaded-coffee and agricultural land-uses which has been attributed to high contents of lignin and polyphenols in both species (Teklay and Malmer (2004). Such patterns of N immobilization in early phases of decomposition has also been reported in similar studies (using leaves from agroforestry species) by Fox et al. (1990), Palm and Sanchez (1991), and Saini and Gupta (2017).

Some other studies also showed the highest amount of N released from an organic material with high quality (high initial N content, low C/N ratio) (Gnankambary et al. 2008; Ibrahim et al. 2018). In this study, millet straw was found to be of low quality, whereas *Acacia tumida* with relatively high N content and lower C/N ratio showed a faster N mineralization (Ibrahim et al. 2018).

The study of Gnankambary et al. (2008) showed that the carbon concentration in remaining litter decreased slightly as decomposition proceeded. The observed that the remaining litter of *F. albida* from the un-mixed litterbags had a C concentration ranging from 40.0% to 47.4% for week 2, and from 37.2% to 42.9% for week 16. For the remaining litter of *V. paradoxa* from the un-mixed litterbags, the C concentration ranged from 48.8% to 52.1% for week 2 and from 46.0% to 51.0% for week 16. In another study, Dawoe et al. (2010) showed lower C to N ratios of 31.6 ± 2.7 for 30-year-old cocoa systems, whereas higher C to N ratios of 42.9 ± 1.5 for 15-year-old cocoa systems.

Asigbaase (2021) quantified and compared the rate of litter decomposition and nutrient mineralization on organic cocoa agroforestry systems to conventional systems in Eastern Region, Ghana. In this study, the high C/N ratio (>25) and low N

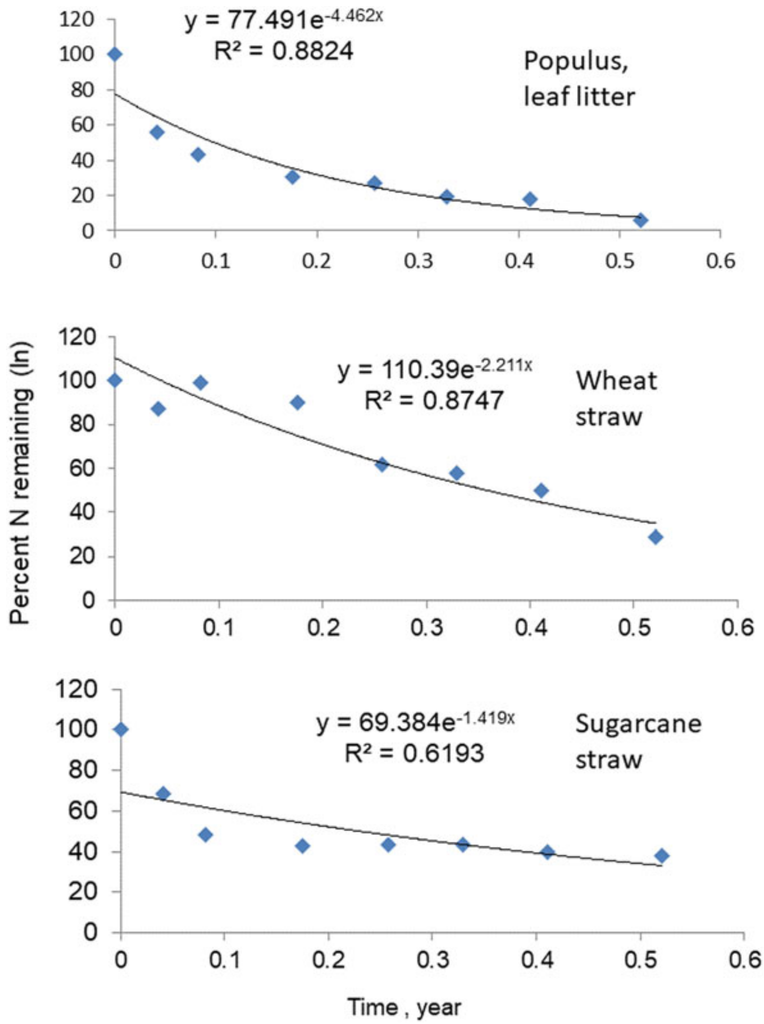

Fig. 16.12 The single exponential model to show relationship between percentage of original nitrogen in residual litter (*Y*) and time (*X*) for Populus leaf litter, wheat straw, and sugarcane straw during 28 April 2004 to 04 November 2004. (Based on data from Saini and Gupta 2017)

content (<2%) indicates that the decomposition on both farms was partly regulated by leaf litter quality (Asigbaase et al. 2021). The study emphasized that the small holder cocoa farmers rely heavily on natural nutrient recycling for soil fertility sustenance in their farms; it is therefore important to understand the dynamics of litter decomposition and nutrient release in organic and conventional cocoa systems for the efficient management of these systems.

In the southern Sudanian zone of Burkina Faso, Cissé et al. (2021) showed that the nutrient release (N, P, and K) was significantly correlated with leaf litter mass decay and degradability from pure and mixed leaf litter of three agroforestry species (*Vitellaria paradoxa*, *Detarium microcarpum* and *Azolla Africana*) under field conditions. In this study, mixing of *A. africana* litter increased the decomposition rate of both *D. microcarpum* and *V. paradoxa* leaf litter; representing a practical biomass management option for farmers to improve nutrient cycling in agroforestry systems.

16.5.3 The Role of Soil Fauna and Microbes in Litter Decomposition

The soil fauna plays important role in conditioning the litter and stimulating microbial action, whereas soil microbes are the main drivers of the decomposition processes (Coleman and Crossley 1996). The decomposer communities in soil include both microorganisms, such as bacteria, fungi and protozoa and macroorganisms like nematodes, mites, collembolans, annelids (i.e. enchytraeids, earthworms) and arthropods, while the mass of decomposer microflora consists primarily of bacteria, fungi, actinomycetes, and yeasts. These microorganisms are very important in bringing about decomposition as 80% of the energy flows through the terrestrial decomposer community (Macfadyen 1963). It has been reported that among the microfauna in leaf litter, fungi are the leading decomposers having greater than 75% potential of reducing organic matter than other microorganisms (Osono 2007; Holden et al. 2013).

16.5.3.1 The Role of Soil Fauna

The soil fauna contributes to the breakdown of litter in many ways: (1) disintegrate plant and animal tissues and make them more easily invadable by microorganisms; (2) selectively decompose and bring about chemical changes in parts of organic residues; (3) form complex aggregates of organic matter of the soil, increasing surface area for bacterial and fungal action (Edwards et al. 1970). Soil fauna can enhance soil organic matter decomposition and nutrient mineralization, and ameliorate soil physical properties (Anderson 1988; Lee 1985). Therefore, judicious manipulation of soil faunal activities may be used to improve the synchronization of nutrient release by mineralization and the crop nutrient demand (Brussaard et al. 1993).

In the agroforestry system integrating *Populus deltoides* and *Leucaena leucocephala* with wheat crop at Kurukshetra in northern India, micro-invertebrate populations were higher during rapid phases of decomposition of *Populus* and *Leucaena* leaf litter; collembola and mites were the dominant group of fauna in the litter bags (Lekha and Gupta 1989). In this study, the collembola population density (*Populus,* 24.3–81.0 per litter bag; *Leucaena* 9.6–95.20 per litter bag) was high during 118 days of decomposition; whereas mites (*Acrina*) showed relatively

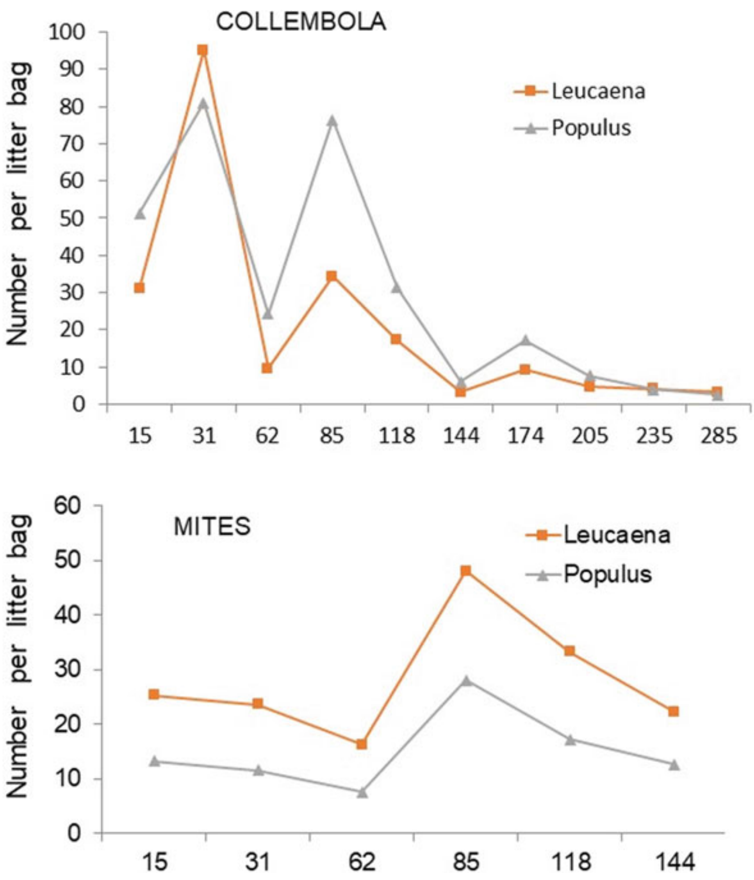

Fig. 16.13 Micro-invertebrate populations in decomposing leaf litter of *Populus* and *Leucaena* in the agroforestry system at Kurukshetra in northern India. (Based on Lekha and Gupta 1989)

lower density (*Populus*, 7.6–28.1 per litter bag; *Leucaena* 16.2–48.1 per litter bag) (Fig. 16.13). Maximum number of collembola per litter bag was: 81.0 ± 26.18, *Populus* leaves; 95.2 *Leucaena* leaves. A mixed group of micro-invertebrates showed higher population density in the later phases of decomposition. The population density of mites and collembola decreased markedly with the progress of litter decomposition from 118 to 285 days. Furthermore, it was evident that populations of micro-invertebrates affected decomposition rates of *Populus* and *Leucaena* leaf litter as mass loss and decomposition rates were significantly higher in 2 mm size bags ($k = 2.7302$–3.71 year^{-1}) as compared to 95 μm mesh bags ($k = 0.76$–1.61 year^{-1}) (Lekha and Gupta 1989).

Several workers have reported that decomposition of low-quality organic residues in tropical ecosystem occurs due to the presence termites (Gupta et al. 1981; Mando and Brussaard 1999; Tian et al. 1995). For instance, the breakdown of *Pennisetum pedicellatum* straw was influenced by termites in northern Burkina Faso during the dry and wet seasons; the contribution of termites to the breakdown of straw was estimated to be more than 70% (Mando and Brussaard 1999).

Tian et al. (1992) studied decomposition and nutrient release patterns of prunings of three woody agroforestry plant species (*Acioa barteri*, *Gliricidia sepium* and *Leucaena leucocephala*), maize (*Zea mays*) stover and rice (*Oryza sativa*) straw under field conditions in the humid tropics, using litterbags of three mesh sizes (0.5, 2 and 7 mm) so as to study the effect of soil fauna. In this study, the decomposition rates of all plant residues in 0.5 mm mesh size litterbags were significantly lower than those in the 2–7 mm mesh-size litterbags. A positive correlation was found between decomposition rate constant and mesh-size of litterbag ($p < 0.057$). Rice straw and maize stover showed the highest decomposition rate in the 2 mm mesh-size litterbag for *Leucaena* and *Gliricidia*. The nutrient release increased with increasing mesh-size of litterbags, suggesting that soil fauna1 activities enhanced nutrient mobilization (Tian et al. 1992).

Tian et al. (1995) developed a plant residue quality index (PRQI) in the (sub-) humid tropics using the C/N ratio and lignin and polyphenol concentration of plant residues. According to this study, a plant residue quality index (PRQI) was defined as: PRQI $=$ [1/(a C/N + b Lignin + c Polyphenols)] $\times$ 100. The field observations showed that termite density was correlated negatively with PRQI across a period of 2 years, whereas ant density was positively correlated with PRQI. While, there was no significant correlation between earthworm density and PRQI in the plant residue-mulched field.

While studying the decomposition rates of leaf litter of different home garden species, Isaac and Nair (2006) observed the permeation of *A. heterophyllus, A. occidentale and M. indica* litter bags by earthworms during the rainy season. In this study, more counts of earthworms were recorded in the fruit tree species litter compared to the others species (*S. macrophylla, A. hirsutus* or in *A. triphysa*) litter bags. The mean number of earthworms (m^3) in soil samples beneath the tree canopies followed the order *Anacardium occidentale* (28.3) > *Artocarpus heterophyllus* (27.7) > *Mangifera indica* (23.7) > *Artocarpus hirsutus* (23.3) > *Swietenia macrophylla* (18.4) > *Ailanthus triphysa* (18.2). According to Tian et al. (1995), earthworms are known to accelerate plant residue decomposition in tropics. They reported the higher faunal activity in *A. heterophyllus, A. occidentale* and *M. indica* litter, which was attributed due to higher quantum of litterfall coupled with favourable soil temperatures and adequate soil moistures in their sub canopies.

Ibrahim et al. (2018) noted a significant correlation between mass loss of millet straw and the termite's population, indicating a significant contribution of termites in straw decomposition. In this study, termites' population was high on millet straw (103 $\pm$ 16), and low on *Acacia tumida* pruning (5 $\pm$ 2), which could be attributed to the foraging behaviour of termites. In another study on the role of the termite, *Odontotermes gurdaspurensis*, for plant decomposition in a tropical grassland, Gupta et al. (1981) showed that the shoot and root materials of *Chenopodium album* were consumed preferentially by termites, while the shoot and rhizome organic residues of *Desmostachya bipinnata* were of low preference and consumed slowly.

16.5.3.2 Role of Microbes

Fungi are known to play a key role leaf litter decomposition, because of their ability to produce a wide range of extracellular enzymes (Zhang et al. 2018). These enzymes help to break down the litter lignocellulose layers that other organisms are unable to decompose (Berg and McClaugherty 2020; Zhang et al. 2018). In particular, the most significant enzymes responsible for the break down substances of the plant cell wall include cellulases, hemicellulases, pectinases, phenol oxidases and polygalacturonases. Some enzymes, such as peptidases, ureases, and phosphatases are important for microbial acquisition of nitrogen and phosphorus (Sinsabaugh et al. 2002; Romaní et al. 2006; Zhang et al. 2018), while phenol oxidases, peroxidases and laccases play an important role in the degradation of lignin (Romaní et al. 2006). Loss of soluble components generally occurs in the first stage, holocellulose decomposition in the second stage, while lignin degradation occurs at the third stage and finally leading to humus formation (Osono 2005, 2007).

The ability of fungal communities to decompose leaf litter has been studied both under field and laboratory conditions in the tropical regions (Promputtha et al., 2002, 2017; Paulus et al. 2006; Duong et al. 2008; Koide et al. 2005; Osono 2005). In these studies, litterbag techniques have been combined with cultivation-based methods followed by the isolation and identification of fungal decomposers. These studies have shown that the overall leaf litter decomposition is a sequential process that initially involves the loss of the less recalcitrant components (i.e. oligosaccharides, organic acids, hemicellulose and cellulose) followed by the degradation of the remaining highly recalcitrant compounds (i.e. lignin, suberin). Furthermore, studies have shown that fungal communities tend to change both quantitatively and qualitatively during the process of decomposition (Promputtha et al. 2002, 2017; Paulus et al. 2006).

Bacteria constitute a group of soil heterotrophs that play key roles in carbon transformations and nutrient cycling, and improving soil fertility. The functional diversity of bacterial colonies is the key to the maintenance of soil biodiversity, stability of food webs and functioning of the ecosystem (Li et al. 2019; Graham et al. 2016). Moreover, the soil environments dominated by bacteria usually have higher pH and nitrogen content that promote plant growth and further stabilize soil cohesion above ground through established vegetation (Madigan et al. 2015).

16.6 Conclusions

The management of soil biodiversity and the soil ecosystem services are central to the sustainability of the agroforestry systems. In recent years, a considerable effort has been made to explore soil biodiversity, soil ecosystem services, and decomposition processes in diverse types of agroforestry systems in Sub-Saharan Africa and Asia for a better understanding of the soil ecosystem functioning. A number of studies discussed in this synthesis have indicated that agroforestry and conservation farming could lead to improvement of biodiversity of soil fauna, arbuscular mycorrhizal fungi, and other soil microorganisms. Agroforestry systems have been shown to increase abundance, biomass and diversity of earthworms compared to crop monocultures. Soil microbes have the capacity to use pools of metabolizable carbon contained in the soil, which is stimulated easily by soil amendments and litter inputs in agroforestry systems. Maintaining active soil invertebrate communities in soils would considerably improve sustainability of agroforestry practice through regulation of soil processes at different scales of time and space.

Agroforestry systems contain a mixture of plant species such as trees and crops that have different growth forms and residue qualities, the residues of mixed quality decompose simultaneously within the same soil matrix and have been found to differ in their pattern of decomposition. However, there is need to undertake long-term studies on diversity soil fauna, and microorganisms, soil ecosystem functions for a better understanding of seasonal, short-term and long-term effects of agroforestry systems. The multifunctional characteristics of agroforestry systems should be taken into account in soil biodiversity management. A better understanding of the positive effects of trees on soils, and an economic analysis in terms of nutrients and other benefits, is an important step towards increasing the use of trees on farms.

References

Adejuyigbe CO, Tian G, Adeoye GO (1999) Soil microbial populations under natural and planted fallows in the humid tropics. Agrofores Syst 47:263–272

Aerts R (1997) Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. Oikos 79:439–449

Akinnifesi FK, Makumba W, Kwesiga F (2006) Sustainable maize production using Gliricidia/ maize intercropping in Southern Malawi. Exp Agr 42:441–457

Akinnifesi FK, Ajayi OC, Sileshi G, Chirwa PW, Chianu J (2010) Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron Sustain Dev 30:615–629

Akinyele AO, Donald-Amaeshi U (2021) Leaf litter decomposition and nutrient release of three selected agroforestry tree species. Agrofor Syst 95:559–570. https://doi.org/10.1007/s10457-021-00606-w

Anderson JM (1988) Invertebrate-mediated transport processes in soils. Agric Ecosystems Environ 24:5–19

Angima SD, Stott DE, O'neill MK, Ong CK, Weesies GA (2002) Use of calliandra Napier grass contour hedges to control erosion in central Kenya. Agri Ecosyst Environ 91:15–23

Asigbaase M, Dawoe E, Sjogersten S, Lomax BH (2021) Decomposition and nutrient mineralisation of leaf litter in smallholder cocoa agroforests: a comparison of organic and conventional farms in Ghana. J Soils Sediments 21:1010–1023. https://doi.org/10.1007/s11368-020-02844-4

Ayuke FO, Brussaard L, Vanlauwe B, Six J, Lelei DK, Kibunja CN, Pulleman MM (2011) Soil fertility management: Impacts on soil macrofauna, soil aggregation and soil organic matter allocation. Appl Soil Ecol 48(1):53–62. https://doi.org/10.1016/j.apsoil.2011.02.001

Bach EM, Ramirez KS, Fraser TD, Wall DH (2020) Soil biodiversity integrates solutions for a sustainable future. Sustainability 12(7):2662. https://doi.org/10.3390/su12072662

Bagyaraj DJ, Thilagar G, Ravisha C, Kushalappa Cheppudira G, Krishnamurthy KN, Philippe V (2015) Below ground microbial diversity as influenced by coffee agroforestry systems in the Western Ghats, India. Agric Ecosyst Environ 202:198–202

Bano R (2006) Soil fauna of rainfed forage farming systems in relation to microclimate and soil fertility. PhD thesis, Bundelkhand University, Jhansi, India

Bardgett RD, van der Putten WH (2014) Belowground biodiversity and ecosystem functioning. Nature 515:505–511

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64:269–285

Barrios E, Sileshi GW, Shepherd K, Sinclair F (2012) Agroforestry and soil health: linking trees, soil biota, and ecosystem services. In: Wall DH, Bardgett RD, Behan-Pelletier V et al (eds) Soil ecology and ecosystem services. Oxford University Press, pp 315–330

Barros NF, Filho CNB (2005) Phosphorus sorption, desorption and resorption by soils of the Brazilian Cerrado supporting eucalypt. Biomass Bioenergy 28:229–236

Battie-Laclau P, Taschen E, Plassard C, Dezette D, Abadie J, Arnal D (2020) Role of trees and herbaceous vegetation beneath trees in maintaining arbuscular mycorrhizal communities in temperate alley cropping systems. Plant Soil 453:1–19

Baveye PC (2021) Bypass and hyperbole in soil research: a personal view on plausible causes and possible remedies. Eur J Soil Sci 72:21–28. https://doi.org/10.1111/ejss.12940

Baveye PC, Baveye J, Gowdy J (2016) Soil 'ecosystem' services and natural capital: critical appraisal of research on uncertain ground. Front Environ Sci 4(41). https://doi.org/10.3389/fenvs.2016.00041

Bayala J, Sileshi G, Coe R, Kalinganire A, Tchoundjeu Z, Sinclair F, Garrity D (2012) Cereal yield response to conservation agriculture practices in drylands of West Africa: a quantitative synthesis. J Arid Environ 78:13–25

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Bayala J, Sanou J, Teklehaimanot Z, Ouedraogo SJ, Kalinganire A, Coe R, Van Noordwijk M (2015) Advances in knowledge of processes in soil-tree-crop interactions in parkland systems in the West African Sahel: a review. Agric Ecosyst Environ 205:25–35. https://doi.org/10.1016/j.agee.2015.02.018

Bayala J, Kalinganire A, Sileshi GW, Tondoh JE (2018) Soil organic carbon and nitrogen in agroforestry systems in sub-Saharan Africa: a review. In: Bationo A (ed) Improving the profitability, sustainability and efficiency of nutrients through site specific fertilizer recommendations in West Africa agro-ecosystems. Springer, Cham. https://doi.org/10.1007/978-3-319-58789-9_4

Berg B, Laskowski R (2006) Litter decomposition: a guide to carbon and nutrient turnover. Adv Ecol Res 38:448

Berg B, McClaugherty C (2020) Plant litter. Decomposition, humus formation, carbon sequestration, 4th edn. Springer, Cham

Berg B, Staaf H (1980) Decomposition rate and chemical changes of Scats pine needle litter. II. Influence of chemical composition. In: Persson T (ed) Structure and function of northern coniferous forests-an ecosystem study, Ecol Bull (Stockholm), vol 32, pp 373–390

Beule L, Corre MD, Schmidt M, Göbel L, Veldkamp E, Karlovsky P (2019) Conversion of monoculture cropland and open grassland to agroforestry alters the abundance of soil bacteria, fungi and soil-N-cycling genes. PLoS One 14:e0218779. https://doi.org/10.1371/journal.pone.0218779

Beule L, Lehtsaar E, Corre MD, Schmidt M, Veldkamp E, Karlovsky P (2020) Poplar rows in temperate agroforestry croplands promote bacteria, fungi, and denitrification genes in soils. Front Microbiol 10:3108. https://doi.org/10.3389/fmicb.2019.03108

Bhadauria T, Ramakrishnan PS (1989) Earthworm population dynamics and contribution to nutrient cycling during cropping and fallow phases of shifting agriculture (Jhum) in North-East India. J Appl Ecol 26:505–520

Blouin M, Hodson ME, Delgado EA, Baker G, Brussaard L, Butt KR, Dai J, Dendooven L, Peres G, Tondoh JE, Cluzeau D, Brun J-J (2013) A review of earthworm impact on soil function and ecosystem services. Eur J Soil Sci 64:161–182. https://doi.org/10.1111/ejss.12025

Boardman J (2006) Soil erosion science: reflections on the limitations of current approaches. Catena 68:73–86. https://doi.org/10.1016/j.catena.2006.03.007

Brümmer G (1978) Funktionen des Bodens im Stoffhaushalt der Ökosphäre. Deutscher Ratfür Landespflege: Zum ökologischen Landbau 31:13–20

Brussaard L (2012) Ecosystem services provided by the soil biota. In: Wall DH, Bardgett RD, Behan-Pelletier V, Herrick JE, Jones TH, Ritz K, Six J, Strong DR, van der Putten WH (eds) Soil ecology and ecosystem services. Oxford University Press, Oxford, pp 45–58

Brussaard L, Hauser S, Tian G (1993) Soil faunal activity in relation to the sustainability of agricultural systems in the humid tropics. In: Mulongoy K, Merckx R (eds) Soil organic matter dynamics and sustainability of tropical agriculture. Wiley, Chichester, pp 241–256

Cadish G, Giller KE (1997) Driven by nature: plant litter quality and decomposition. CAB International, Wallingford

Campbell EE, Parton WJ, Soong JL, Paustian K, Hobbs NT, Cotrufo MF (2016) Using litter chemistry controls on microbial processes to partition litter carbon fluxes with the litter decomposition and leaching (LIDEL) model. Soil Biol Biochem 100:160–174

Cardinael R, Hoeffner K, Chenu C, Chevallier T, Béral C, Dewisme A, Cluzeau D (2019) Spatial variation of earthworm communities and soil organic carbon in temperate agroforestry. Biol Fertil Soils 55:171–183

Cardinael R, Mao Z, Chenu C, Hinsinger P (2020) Belowground functioning of agroforestry systems: recent advances and perspectives. Plant Soil 453:1–13. https://doi.org/10.1007/s11104-020-04633-x

Cardoso IM, Kuyper TW (2006) Mycorrhizas and tropical soil fertility. Agric Ecosyst Environ 116: 72–84

Cardoso IM, Boddington C, Janssen BH, Oenema O, Kuyper TW (2003) Distribution of mycorrhizal fungal spores in soils under agroforestry and monocultural coffee systems in Brazil. Agrofor Syst 58:33–43

Cerda R, Orozco-Aguilar L, Sepúlveda N, Ordoñez J, Carreño-Rocabado G, Amores F, Caicedo W, Oblitas S, Somarriba E (2019) Tropical agroforestry and ecosystem services: trade-off analysis for better design strategies. Agroforestry for Sustainable Agriculrture, Burleigh Dodds Science Publishing Limited, pp 467–509. https://doi.org/10.19103/as.2018.0041.24

Chatterjee N, Nair PKR, Chakraborty S, Nair VD (2018) Changes in soil carbon stocks across the forest-agroforest-agriculture/pasture continuum in various agroecological regions: a meta-analysis. Agric Ecosyst Environ 266:55–67. https://doi.org/10.1016/j.agee.2018.07.014

Cissé M, Traoré S, Bationo BA (2021) Decomposition and nutrient release from the mixed leaf litter of three agroforestry species in the Sudanian zone of West Africa. SN Appl Sci 3:273. https://doi.org/10.1007/s42452-021-04242-y

Coleman DC, Crossley DA (1996) Fundamental of soil ecology. Academic Press Inc, New York, p 205

Dagar JC (1995) Agroforestry systems for the Andaman & Nicobar Islands. Int Tree Crops J 8:107–128

Dagar JC, Gupta SR (2020) Agroforestry interventions for rehabilitating salt-affected and waterlogged marginal landscapes. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes-recent advances and emerging challenges, vol 2. Springer, Singapore, pp 111–162

Dagar JC, Pandey CB, Chaturvedi CS (2014a) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services, advances in agroforestry, vol 10. Springer, Dordrecht, pp 185–232

Dagar JC, Singh AK, Arunachalam A (eds) (2014b) Agroforestry systems in India: livelihood security and ecosystem services. Advances in agroforestry, vol 10. Springer, Dordrecht, p 400

Dagar JC, Gangaiah B, Gupta SR (2020a) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes-recent advances and emerging challenges, vol 1. Springer, Singapore, pp 367–424

Dagar JC, Sileshi WG, Akinnifesi FK (2020b) Agroforestry to enhance livelihood security in Africa: research trends and emerging challenges. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore. https://doi.org/10.1007/978-981-15-6807-7_5

Daily GC (1997) Nature's services: societal dependence on natural ecosystems. Island, Washington, DC

Das T, Das AK (2010) Litter production and decomposition in the forested areas of traditional home gardens: a case study from Barak Valley, Assam, northeast India. Agrofor Syst 79:157–170. https://doi.org/10.1007/s10457-010-9284-0

Dawoe EK, Isaac ME, Quashie-Sam J (2010) Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. Plant Soil 330:55–64

Decaëns T, Jiménez JJ, Gioia C, Measey GJ, Lavelle P (2006) The values of soil animals for conservation biology. Eur J Soil Biol 42:S23–S38

Dominati E, Patterson M, Mackay A (2010) A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol Econ 69:1858–1868

Dominati E, Mackay A, Green S, Patterson M (2014) A soil change-based methodology for the quantification and valuation of ecosystem services from agro-ecosystems: a case study of pastoral agriculture in New Zealand. Ecol Econ 100:119–129

Duong LM, McKenzie EHC, Lumyong S, Hyde KD (2008) Fungal succession on senescent leaves of *Castanopsis diversifolia* in Doi Suthep-Pui National Park, Thailand. Fungal Divers 30:23–36

Edwards CA, Reichte DE, Crossley DA Jr (1970) The role of soil invertebrates in turnover of organic matter and nutrients. In: Reichle DE (ed) Analysis of temperate forest ecosystems. Springer, New York, pp 147–172

FAO (2005) Land and environmental degradation and desertification in Africa. Food and Agricultural Organization, Rome

FAO (2015) Status of the world's soil resources, Intergovernmental Technical Panel on Soils, pp 123–126. http://www.fao.org/3/a-i5199e.pdf

FAO, ITPS, GSBI, SCBD, EC (2020) State of knowledge of soil biodiversity - Status, challenges and potentialities. Report, 2020. FAO, Rome, Italy

Fox RH, Myers RJK, Vallis I (1990) The nitrogen mineralization rate of legume residues in soils as influenced by their polyphenol, lignin and nitrogen contents. Plant Soil 129:251–259

Garcia C, Marie-Vivien D, Kushalappa CG, Chengappa PG, Nanaya KM (2007) Geographical indications and biodiversity in the Western Ghats: can labelling benefit producers and the environment in a mountain agroforestry landscape? Mt Res Dev 27:206–210

Garcia CA, Bhagwat SA, Ghazoul J, Nath CD, Nanaya KM, Kushalappa CG, Raghuramulu Y, Nasi R, Vaast P (2010) Biodiversity conservation in agricultural landscapes: challenges and opportunities of coffee agroforests in the Western Ghats, India. Conserv Boil 24(2):479–488

Gaur A (2013) Plant biomass soil microbial activity and carbon sequestration in agroforestry systems. PhD Thesis, Botany Department. Kurukshetra University, Kurukshetra, 278pp

Gaur A, Gupta SR (2012) Impact of agroforestry systems on carbon sequestration in Northern Haryana, India. Int J Ecol Environ Sci 38(2–3):73–85

Giller KE, Bignell D, Lavelle P, Swift M, Barrios E, Moreira F, van Noordwijk M, Barios I, Karanja N, Huising J (2005) Soil biodiversity in rapidly changing tropical landscapes: scaling down and scaling up. In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, pp 295–318

Girma D, Addis T, Tadele T (2009) Effect of mulching and intercropping on termite damage to maize at Bako, Western Ethiopia. Pest Manag J Ethiop 13:38–43

Gnankambary Z, Bayala J, Malmer A, Nyberg G, Hien V (2008) Decomposition and nutrient release from mixed plant litters of contrasting quality in an agroforestry parkland in the south-Sudanese zone of West Africa. Nutr Cycl Agroecosyst 82(1):1–13. https://doi.org/10.1007/s10705-008-9165-3

Graham EB, Knelman JE, Schindlbacher A, Siciliano S, Breulmann M, Yannarell A, Beman JM, Abell G, Philippot L, Prosser J, Foulquier A, Yuste JC, Glanville HC, Jones DL, Angel R, Salminen J, Newton RJ, Bürgmann H, Ingram LJ, Hamer U, Siljanen HMP, Peltoniemi K, Potthast K, Bañeras L, Hartmann M, Banerjee S, Yu R-Q, Nogaro G, Richter A, Koranda M, Castle SC, Goberna M, Song B, Chatterjee A, Nunes OC, Lopes AR, Cao Y, Kaisermann A, Hallin S, Strickland MS, Garcia-Pausas J, Barba J, Kang H, Isobe K, Papaspyrou S, Pastorelli R, Lagomarsino A, Lindström ES, Basiliko N, Nemergut DR (2016) Microbes as engines of ecosystem function: when does community structure enhance predictions of ecosystem processes? Front Microbiol 7:214. https://doi.org/10.3389/fmicb.2016.00214

Gupta SR, Rajvanshi R, Singh JS (1981) The role of termite *Odentotermes gurdaspurensis (Isoptera: Termitidae)* in plant decomposition in a tropical grassland. Pedobiologia 22:254–261

Gupta N, Kukal SS, Bawa SS, Dhaliwal GS (2009) Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. Agrofor Syst 76:27–35

Gupta SR, Jangra R, Asha G, Dagar JC (2019) Tree-based systems for enhancing environmental services of saline environments. In: Dagar JC, Yadav RK, Sharma PC, Sharma DK (eds) Research developments in saline agriculture. Springer, Singapore, pp 461–502

Hailemariam M, Birhane E, Asfaw Z, Zewdie S (2013) Arbuscular mycorrhizal association of indigenous agroforestry tree species and their infective potential with maize in the rift valley, Ethiopia. Agrofor Syst 87(6):1261–1272. https://doi.org/10.1007/s10457-013-9634-9

Haines-Young R, Potschin MB (2017) Common international classification of ecosystem services (CICES) V5.1 and guidance on the application of the revised structure. www.cices.eu

Hairiah K, Sulistyani H, Suprayogo D, Widianto PP, Widodo RH, Van Noordwijk M (2006) Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung. For Ecol Manag 224:45–57. https://doi.org/10.1016/j.foreco.2005.12.007

Handayanto E, Cadisch G, Giller KE (1994) Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. Plant Soil 160:237–248

Hasanuzzaman MD, Hossain M (2014) Leaf litter decomposition and nutrient dynamics associated with common horticultural cropland agroforest tree species of Bangladesh. Int J For Res. https://doi.org/10.1155/2014/805940

Hauser S (1993) Distribution and activity of earthworms and contribution to nutrient recycling in alley cropping. Biol Fertil Soils 15:16–20

Haygarth PM, Ritz K (2009) The future of soils and land use in the UK: soil systems for the provision of land-based ecosystem services. Land Use Policy 26:S187–S197

Heal OW, Anderson JM, Swift MJ (1997) Plant litter quality and decomposition: an historical overview. In: Cadisch G, Giller KE (eds) Driven by nature: plant litter quality and decomposition. CAB International, Wallingford, pp 3–30

Holden SR, Gutierrez A, Treseder K (2013) Changes in soil fungal communities, extracellular enzyme activities, and litter decomposition across a fire chronosequence in Alaskan boreal forests. Ecosystems 16:34–46

Holland EA, Coleman DC (1987) Litter placement effects on microbial and organic matter dynamics in an agroecosystem. Ecology 68:425–433. https://doi.org/10.2307/1939274

Hossain M, Siddique MRH, Rahman S, Hossain Z, Hasan M (2011) Nutrient dynamics associated with leaf litter decomposition of three agroforestry tree species (*Azadirachta indic*a, *Dalbergia sissoo*, and *Melia azedarach*) of Bangladesh. J For Res 22(4):577–582. https://doi.org/10.1007/s11676-011-0175-7

Ibrahim A, Abaidoo RC, Iliasso ADKT, Fatondji D (2018) Nutrient release dynamics from decomposing organic materials and their mulching-effect on pearl millet yields in a low-input Sahelian cropping system. Nutr Cycl Agroecosyst 112:1–15

Ingram LJ, Schuman GE, Stahl PD, Spackman LK (2005) Microbial respiration and organic carbon indicate nutrient cycling recovery in reclaimed soils. Soil Sci Soc Am J 69:1737–1745

Isaac SR, Nair MA (2006) Litter dynamics of six multipurpose trees in a homegarden in Southern Kerala, India. Agrofor Syst 67:203–213

IUSS (2014) World Reference Base for Soil Resources International soil classification system for naming soils and creating legends for soil maps World Soil Resources Reports No. 106, Food and Agricultural Organization, Rome

Jenkinson DS, Ladd JN (1981) Microbial biomass in soil; measurement and turnover. In: Paul EA, Ladd JN (eds) Soil biochemistry, vol 5. Marcel Dekker, New York, pp 415–471

Jenny H, Gessel SP, Bingham FT (1949) Comparative study of decomposition rates of organic matter in temperate and tropical regions. Soil Sci 68:419–432

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386

Jouquet P, Chaudhary E, Kumar ARV (2018) Sustainable use of termite activity in agro-ecosystems with reference to earthworms: a review. Agron Sustain Dev 38:3. https://doi.org/10.1007/s13593-017-0483-1

Julka JM, Paliwal R (2005) Distribution of earthworms in different agro-climatic region of India. In: Ramakrishnan PS, Saxena KG, Swift MJ, Rao KS, Maikhuri RK (eds) Soil biodiversity, ecological processes and landscape. Oxford and ABH Publications Co. Pvt. Ltd., New Delhi, pp 3–13

Kamau S, Barrios E, Karanja NK, Ayuke FO, Lehmann J (2017) Soil macrofauna abundance under dominant tree species increases along a soil degradation gradient. Soil Biol Biochem 112:35–46

Kamau S, Barrios E, Karanja NK, Ayuke FO, Lehmann J (2020) Dominant tree species and earthworms affect soil aggregation and carbon content along a soil degradation gradient in an agricultural landscape. Geoderma 359:113983. https://doi.org/10.1016/j.geoderma.2019.113983

Kang BT (1993) Alley cropping: past achievements and future directions. Agrofor Syst 23:141–155

Kang BT, Ghuman BS (1991) Alley cropping as a sustainable system. In: Moldenhaver WC, Hudson NW, Sheng TC, Lee SW (eds) Development of conservation farming on hillslopes. Soil & Water Conservation Society, Ankeny, pp 172–184

Kang BT, Reynolds L, Atta-Krah AN (1990) Alley cropping. Adv Agron 43:315–359

Kaonga ML, Bailey-Smith TP (2009) Carbon pools in tree biomass and the soil in improved fallows in eastern Zambia. Agrofor Syst 76:37–51

Kaur B, Gupta SR, Singh G (2000) Soil carbon, microbial activity and nitrogen availability in agroforest system on moderately alkaline soils in northern India. Appl Soil Ecol 15:283–294

Kaur B, Gupta SR, Singh G (2002a) Carbon storage and nitrogen cycling in silvi-pastoral systems on a sodic soil in northwestern India. Agrofor Syst 54:21–29

Kaur B, Gupta SR, Singh G (2002b) Bioamelioration of a sodic soil by silvopastoral system in northwestern India. Agrofor Syst 54:13–20

Keesstra SD, Geissen V, Mosse K, Piirainen S, Scudiero E, Leistra M, van Schaik L (2012) Soil as a filter for groundwater quality. Curr Opin Environ Sustain 4:507–516. https://doi.org/10.1016/j.cosust.2012.10.007

Kennedy AC, Gewin VL (1997) Soil microbial diversity: present and future consideration. Soil Sci 162:607–617

Kihara J, Martius C, Bationo A (2015) Crop residue disappearance and macrofauna activity in sub-humid western Kenya. Nutr Cycl Agroecosyst 102(1):101–111

Kimenju JW, Karanja NK, Nyongesa MW (2004) Diversity and abundance of nematodes in agroecosystems of Kenya. J Trop Microbiol 3:24–33

Koide K, Osono T, Takeda H (2005) Fungal succession and decomposition of *Camellia japonica* leaf litter. Ecol Res 20:599–609

Kumari C, Gupta SR, Dagar JC, Singh V, Kumar M (2018) Carbon sequestration and microbial biodiversity in saline water irrigated agroforestry systems of semiarid hyperthermic Camborthids regions of North-West India. J Soil Salinity Water Qual 10(2):133–148

Kuyah S, Whitney C, Jonsson M, Sileshi G, Öborn I, Muthuri C, Luedeling E (2019) Can agroforestry enhance ecosystem services provision without reducing productivity? In: Dupraz C, Gosme M, Lawson G (eds) Book of abstracts, 4th world congress on agroforestry. Agroforestry: strengthening links between science, society and policy. CIRAD, INRA, World Agroforestry, Montpellier, p 323

Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Kuntashula E, Dimobe K, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Agroforestry for degraded landscapes. Springer, Berlin, pp 135–167

Lakshmi G, Joseph A (2017) Soil microarthropods as indicators of soil quality of tropical home gardens in a village in Kerala, India. Agrofor Syst 91:439–450

Lakshmi G, Joseph A (2020) Soil microarthropods as indicators of soil health of tropical home gardens in Kerala, India. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore, pp 525–538. https://doi.org/10.1007/978-981-15-4136-0_17

Lal R (1989) Agroforestry systems and soil surface management of a tropical alfisol. Agrofor Syst 8:97–111

Lal R (1996) Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. III. Runoff soil erosion and nutrient loss. Land Degrad Dev 7:99–119

Lal R (2018) Sustainable intensification of China's agroecosystems by conservation agriculture. Int Soil Water Conserv Res 6(1):1–12

Laossi KR, Barot S, Carvalho D, Desjardins T, Lavelle P, Martins M, Mitja D, Rendeiro AC, Rousseau G, Sarrazin M, Velasquez E, Grimaldi M (2008) Effects of plant diversity on plant biomass production and soil macrofauna in Amazonian pastures. Pedobiologia 51:397–407

Lavelle P (1997) Faunal activities and soil processes: adaptive strategies that determine ecosystem function. In: Begon M, Fitter AH (eds) Adv Ecol Res, vol 27, pp 93–132

Lavelle P, Dangerfield M, Fragoso C, Eschenbrenner V, López-Hernández D, Pashanasi B (1994) The relationship between soil macrofauna and tropical soil fertility. In: Woomer PL, Swift MJ (eds) The biological management of tropical soil fertility. Wiley, Chichester, pp 137–169

Lavelle P, Bignell D, Lepage M, Wolters V, Roger P, Ineson P, Heal OW, Dhillion S (1997) Soil function in a changing world: the role of invertebrate ecosystem engineers. Eur J Soil Biol 33: 159–193

Lavelle P, Decaëns T, Aubert M, Barot S, Blouin M, Bureau F, Margerie P, Mora P, Rossi J-P (2006) Soil invertebrates and ecosystem services. Eur J Soil Biol 42:S3–S15

Lavelle P, Spain A, Blouin M, Brown G, Decaëns T, Grimaldi M, Jiménez JJ, McKey D, Mathieu J, Velasquez E, Zangerlé A (2016) Ecosystem engineers in a self-organized soil. Soil Sci 181(3/4): 91–109. https://doi.org/10.1097/SS.0000000000000155

Lee KE (1985) Earthworms: their ecology and relationships with soils and land use. Academic Press Inc, London, p 411

Lee KE, Wood TG (1971) Termites and soils. Academic Press, London, p 251

Lehmann J, Günther D, Socorro da Mota M, Pereira de Almeida M, Zech W, Kaiser K (2001) Inorganic and organic soil phosphorus and sulfur pools in an Amazonian multistrata agroforestry system. Agrofor Syst 53:113–124. https://doi.org/10.1023/A:1013364201542

Lekha A, Gupta SR (1989) Decomposition of *Populus* and *Leucaena* leaf litter in an agroforestry system. Int J Ecol Environ Sci 15:97–108

Lepage MG (1981) Étude de la prédation de *Megaponera foetens* (F.) surles populations récoltantes de Macrotermitinae dans un ecosystème semi-aride (Kajiado-Kenya). Insect Soc 28(3):247–262

Li Z, Tian D, Wang B, Wang J, Wang S, Chen HYH, Xu X, Wang C, He N, Niu S (2019) Microbes drive global soil nitrogen mineralization and availability. Glob Change Biol 25:1078–1088

Lousier JD, Parkinson D (1976) Litter decomposition in a cool temperate deciduous forest. Can J Bot 54:419–436

Ludelling E, Sileshi G, Beedy T, Dietz J (2011) Carbon sequestration potential by agroforestry in Africa. In: Kumar BM, Nair PKR (eds) Carbon sequestration in agroforestry systems. Springer, The Netherlands, pp 61–83

Lundgren B, Raintree JB (1983) Sustained agroforestry. In: Nestel B (ed) Agricultural research for development: potentials and challenges in Asia. ISNAR, The Hague

Macfadyen A (1963) The contribution of the microfauna to total soil metabolism. In: Decksen J, van der Drift J (eds) Soil organisms. North Holland, Amsterdam, pp 3–17

Madigan MT, Martinko JM, Bender KS, Buckley DH, Stahl DA (2015) Brock biology of microorganisms, 14th edn. Pearson Education, Inc, New York

Mafongoya PL, Sileshi GW (2020) Indices to identify and quantify ecosystem services in sustainable food systems. In: Rusinamodzi L (ed) The role of ecosystem services in sustainable food systems. Elsevier Inc., pp 43–71. https://doi.org/10.1016/B978-0-12-816436-5.00003-2

Mafongoya PL, Dzowela BH, Nair PKR (1997) Effect of multipurpose trees, age of cutting and drying method on pruning quality. In: Cadisch G, Giller KE (eds) Driven by nature: plant litter quality and decomposition. CAB International, Wallingford, UK, pp 167–174

Mafongoya PL, Giller KE, Palm CA (1998) Decomposition and nitrogen release pattern of tree prunings and litter. Agrofor Syst 38:77–97. https://doi.org/10.1023/A:1005978101429

Mahari A (2014) Leaf litter decomposition and nutrient release from *Cordia africana* Lam. and *Croton Macrostachyus* Del. tree species. J Environ Earth Sci 4:1–7

Mando A, Brussaard L (1999) Contribution of termites to the breakdown of straw under Sahelian conditions. Biol Fertil Soils 29:332–334

Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr Opin Environ Sustain 6:8–14. https://doi.org/10.1016/j.cosust.2013.09.002

Marsden C, Martin-Chave A, Cortet J, Hedde M, Capowiez Y (2020) How agroforestry systems influence soil fauna and their functions—a review. Plant Soil 453:29–44

MEA (Millennium Ecosystem Assessment) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Melillo JM, Aber JD, Muratore JM (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621–626

Montanarella L, Pennock DJ, McKenzie NJ, Badraoui M, Chude V, Baptista I, Mamo T, Yemefack M, Singh Aulakh M, Yagi K, Suk YH, Vijarnsorn P, Zhang G-L, Arrouays D, Black H, Krasilnikov P, Sobocká J, Alegre J, Henriquez CR, de Lourdes M-SM, Taboada M, Espinosa-Victoria D, AlShankiti A, AlaviPanah Sayed K, Elsiddig Ahmed El Mustafa E, Hempel J, Marta Camps A, Nachtergaele F, Vargas R (2015) World's soils are under threat. Soil Discuss 2:1263–1272

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Nat Acad Sci U S A 104: 13268–13272

Muchane MN, Sileshi GW, Jonsson M, Pumariño L, Barrios E (2020) Agroforestry boosts soil health in the humid and sub-humid tropics: a meta-analysis. Agric Ecosyst Environ 295:106899. https://doi.org/10.1016/j.agee.2020.106899

Mugerwa S (2015a) Magnitude of the termite problem and its potential anthropogenic causes in Nakasongola district of Uganda. Grassl Sci 61(2):75–82. https://doi.org/10.1111/grs.12087

Mugerwa S (2015b) Infestation of African savanna ecosystems by sub-terranean termites. Ecol Complex 21:70–77

Muleta D, Assefa F, Nemomissa S, Granhall U (2007) Composition of coffee shade tree species and density of indigenous arbuscular mycorrhizal fungi (AMF) spores in Bonga natural coffee forest southwestern Ethiopia. For Ecol Manag 241:145–154

Muleta D, Assefa NS, Granhall U (2008) Distribution of arbuscular mycorrhizal fungi spores in soils of smallholder agroforestry and monocultural coffee systems in southwestern Ethiopia. Biol Fertil Soils 44:653–659

Mulia R, Hoang SV, Dinh VM, Duong NBT, Nguyen AD, Lam DH, Thi Hoang DT, van Noordwijk M (2021) Earthworm diversity, forest conversion and agroforestry in Quang Nam Province, Vietnam. Land 10(36). https://doi.org/10.3390/land10010036

Mungai NW, Motavalli PP, Kremer RJ, Nelson KA (2005) Spatial variation of soil enzyme activities and microbial functional diversity in temperate alley cropping systems. Biol Fertil Soils 42:129–136. https://doi.org/10.1007/s00374-005-0005-1

Munthali MG, Gachene CKK, Karanja NK, Sileshi GW (2015) Decomposition rates and nutrient release patterns of *Tephrosia vogelii* and *Tephrosia candida* residues in Malawi. Int J Pl Res 1: 26–35

Nair PKR (1985) Classification of agroforestry systems. Agrofor Syst 3:97–128. https://doi.org/10.1007/BF00122638

Nair PK, Garrity D (2012) Agroforestry—the future of global land use. Advances in agroforestry book series. Springer, Berlin

Nair PKR, Kumar BM, Nair VD (2021) An introduction to agroforestry: four decades of scientific developments, 2nd edn. Springer International Publishing

Nath AJ, Das AK (2011) Decomposition dynamics of three priority bamboo species of homegardens in Barak Valley, Northeast India. Int Soc Trop Ecol 52:325–330

Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Dev 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831

Negash M, Starr M (2021) Litter decomposition of six tree species on indigenous agroforestry farms in south-eastern Ethiopia in relation to litterfall carbon inputs and modelled soil respiration. Agrofor Syst 95:755–766

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319–337

Okwakol MJN, Sekamatte MB (2007) Soil macrofauna research in ecosystems in Uganda. Afr J Ecol 45:2–8

Olson JA (1963) Energy storage and the balance of producers and decomposers in ecological system. Ecology 44:322–331

Orgiazzi A, Bardgett RD, Barrios E, Behan-Pelletier V, Briones MJI, Chotte J-L, Deyn D, Gerlinde B, Eggleton P, Fierer N, Fraser T, Hedlund K, Jeffery S, Johnson NC, Jones A, Kandeler E, Kaneko N, Lavelle P, Lemanceau P, Miko L, Montanarella L, Moreira FMS, Ramirez KS, Scheu S, Singh BK, Six J, van der Putten WH, Wall DH (2016) Global soil biodiversity atlas. Publications Office of the European Union, Luxembourg

Osono T (2005) Colonization and succession of fungi during decomposition of *Swida controversa* leaf litter. Mycologia 97:589–597

Osono T (2007) Ecology of ligninolytic fungi associated with leaf litter decomposition. Ecol Res 22:955–974

Palm CA, Sanchez PA (1991) Nitrogen release from some leaves of tropical legume as affected by their lignin and polyphenolic contents. Soil Biol Biochem 23:83–88

Palm CA, Sanchez PA, Ahamed S, Awiti A (2007) Soils: a contemporary perspective. Annu Rev Environ Resour 32:99–129

Palmer J, Thorburn PJ, Biggs JS, Dominati EJ, Probert ME, Meier EA, Huth NI, Dodd M, Snow V, Larsen JR, Parton WJ (2017) Nitrogen cycling from increased soil organic carbon contributes both positively and negatively to ecosystem services in wheat agro-ecosystems. Front Plant Sci 8:731. https://doi.org/10.3389/fpls.2017.00

Pande M, Tarafdar JC (2004) Arbuscular mycorrhizal fungal diversity in neem-based agroforestry systems in Rajasthan. Appl Soil Ecol 26(3):233–241. https://doi.org/10.1016/j.apsoil.2003.12.009

Paulus B, Gadek P, Hyde KD (2006) Successional patterns of microfungi in fallen leaves of *Ficus pleurocarpa* (Moraceae) in an Australian tropical rain forest. Biotropica 38:42–51

Powlson DS, Brookes PC, Christensen BT (1987) Measurement of soil microbial biomass provides an early indication of change in total soil organic matter due to straw incorporation. Soil Biol Biochem 19:159–164

Prescott CE, Zabek LM, Staley CL, Kabzems R (2000) Decomposition of broad leaf and needle litter in forests of British Columbia: influences of litter type, forest type and litter mixtures. Can J For Res 30:1742–1750

Price GW, Gordon AM (1999) Spatial and temporal distribution of earthworms in a temperate intercropping system in southern Ontario, Canada. Agrofor Syst 44:141–149

Promputtha I, Lumyong S, Lumyong P, McKenzie EHC, Hyde KD (2002) Fungal succession on senescent leaves of *Manglietia garrettii* in Doi Suthep-Pui National Park, northern Thailand. Fungal Divers 10:89–100

Promputtha I, McKenzie EH, Tennakoon DS, Lumyong S, Hyde KD (2017) Succession and natural occurrence of saprobic fungi on leaves of *Magnolia liliifera* in a tropical forest. Cryptogam Mycol 38:213–225

Pumariño L, Sileshi GW, Gripenberg S, Kaartinen R, Barrios E, Muchane MN, Midega C, Jonsson M (2015) Effects of agroforestry on pest, disease and weed control: a meta-analysis. Basic Appl Ecol 16:573–582

Purwaningsih R, Sartohadi J, Setiawan MA (2020) Trees and crops arrangement in the agroforestry system based on slope units to control landslide reactivation on volcanic foot slopes in Java, Indonesia. Land 9(9):327. https://doi.org/10.3390/land9090327

Rahman PM, Varma RV, Sileshi GW (2012) Abundance and diversity of soil invertebrates in annual crops, agroforestry and forest ecosystems in the Nilgiri biosphere reserve of Western Ghats, India. Agrofor Syst 85:165–177

Rajagopal D, Ali TMM (1984) Predatory ants of the mound building termite, *Odontotermes wallonensis* (Wasmann) with special reference to the predatory behaviour of *Leptogenys processionalis* (Jerdon). J Bombay Nat Hist Soc 81:721–725

Rajkhowa DJ, Bhattacharyya PN, Sarma AK, Mahanta K (2015) Diversity and distribution of earthworms in different soil habitats of Assam, North-East India, an Indo-Burma biodiversity hotspot. Proc Natl Acad Sci India B-Biol Sci 85:389–396

Rao MR, Nair PKR, Ong CK (1998) Biophysical interactions in tropical agroforestry systems. Agrofor Syst 38:3–50

Rigal C, Xu J, Vaast P (2020) Young shade trees improve soil quality in intensively managed coffee systems recently converted to agroforestry in Yunnan Province, China. Plant Soil 453:119–137. https://doi.org/10.1007/s11104-019-04004-1

Rizvi RH, Dhyani SK, Yadav RS, Singh R (2011) Biomass production and carbon stock of poplar agroforestry systems in Yamunanagar and Saharnpur districts of north-western India. Curr Sci 100:736–742

Rizvi RH, Handa AK, Sridhar KB, Singh RK, Dhyani SK, Rizvi J, Dongre G (2020) Spatial analysis of area and carbon stocks under *Populus deltoides* based agroforestry systems in Punjab and Haryana states of Indo-Gangetic Plains. Agrofor Syst 94:2185–2197. https://doi.org/10.1007/s10457-020-00540-3

Rodrigues AF, Latawiec AE, Reid BJ, Solórzano A, Schuler AE, Lacerda C, Fidalgo ECC, Scarano FR, Tubenchlak F, Pena I, Vicente-Vicente JL, Korys KA, Cooper M, Fernandes NF, Prado RB, Maioli V, Dib V, Teixeira WG (2021) Systematic review of soil ecosystem services in tropical regions. R S Open Sci 8:201584. https://doi.org/10.1098/rsos.201584

Romaní AM, Fischer H, Mille-Lindblom C, Tranvik LJ (2006) Interactions of bacteria and fungi on decomposing litter: differential extracellular enzyme activities. Ecology 87:2559–2569

Roy S, Saxena P, Roy MM (2008) Soil biodiversity under forage production systems. IGFRI, Jhansi, p 45

Roy S, Roy MM, Bano R, Saxena P (2017) Soil microarthropods: biodiversity and role in grassland and agroforestry ecosystems. In: Dagar J, Tewari V (eds) Agroforestry: anecdotal to modern science. Springer, Singapore. https://doi.org/10.1007/978-981-10-7650-3_26

Saha SK, Nair PKR, Nair VD, Kumar BM (2009) Soil carbon stock in relation to plant diversity in Kerala, India. Agrofor Syst 76:53–65

Saini R, Gupta SR (2017) Litter decomposition and nitrogen release pattern in *Populus deltoides* agrisilviculture agroforestry system in Northern India. Ind J Sci 24(94):514–528

Saini R, Gupta SR (2018) Diversity of arbuscular mycorrhizal fungi in *Populus deltoides* agroforestry systems at Kurukshetra in Northern India. Int Res J Biol Sci 7(2):1–7

Sakala WD, Cadisch G, Giller KE (2000) Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol Biochem 32:679–688

Sands W (1977) Role of termites in tropical agriculture. Outlook Agric 9(3):136–143. https://doi.org/10.1177/003072707700900

Sekamatte BM, Ogenga-Latigo M, Russell-Smith A (2003) Effects of maize–legume intercrops on termite damage to maize, activity of predatory ants and maize yields in Uganda. Crop Prot 22(1): 87–93. https://doi.org/10.1016/S0261-2194(02)00115
Senapati BK, Julka JM, Lavelle P (2005) Impact of land use and cover change on soil fauna in south and south east India. In: Ramakrishnan PS, Saxena KG, Swift MJ, Rao KS, Maikhuri RK (eds) Soil biodiversity, ecological process and landscape management. Oxford & IBH, pp 67–76
Setälä HM, Francini G, Allen JA, Hui N, Jumpponen A, Kotze DJ (2016) Vegetation type and age drive changes in soil properties, nitrogen, and carbon sequestration in urban parks under cold climate. Front Ecol Evol 4:1–14. https://doi.org/10.3389/fevo.2016.00093
Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11(4):368. https://doi.org/10.3390/f11040368
Shivashankar T, Rajagopal D, Veeresh GK (1991) Termites have their choice of food in the midst of plenty. In: Veeresh GK, Rajagopal D, Viraktamath CA (eds) Advances in management and conservation of soil fauna. Proceedings of the 10th international soil zoology colloquium, Bangalore, August 7–13, 1988. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, pp 127–135
Sileshi WG, Mafongoya PL (2006a) The short-term impact of forest fire on soil invertebrates in the miombo. Biodiv Conserv 15:3153–3160
Sileshi WG, Mafongoya PL (2006b) Long-term effect of legume improved fallows on soil invertebrates and maize yield in eastern Zambia. Agri Ecosyst Environ 115:69–78
Sileshi WG, Mafongoya PL (2007) Quantity and quality of organic inputs from coppicing leguminous trees influence abundance of soil macrofauna in maize crops in eastern Zambia. Biol Fertil Soils 43:333–340. https://doi.org/10.1007/s00374-006-0111-8
Sileshi WG, Akinnifesi FK, Ajayi OC, Chakeredza S, Kaonga M, Matakala P (2007) Contribution of agroforestry to ecosystem services in the miombo eco-region of eastern and southern Africa. Afr J Environ Sci Technol 1(4):068–080
Sileshi WG, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307:1–19
Sileshi WG, Akinnifesi FK, Mafongoya PL, Kuntashula E, Ajayi OC (2020a) Potential of Gliricidia-based agroforestry systems for resource limited agro-ecosystems. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes. Springer, Singapore. https://doi.org/10.1007/978-981-15-6807-7_5
Sileshi WG, Mafongoya PL, Nath AJ (2020b) Agroforestry systems for improving nutrient recycling and soil fertility on degraded lands. In: Dagar JC et al (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1. Springer, Singapore, pp 225–254. https://doi.org/10.1007/978-981-15-4136-0_8
Singh JS, Gupta SR (1977) Plant decomposition and soil respiration in terrestrial ecosystem. Bot Rev 43:449–528
Singh JS, Raghubanshi AS, Singh RS, Srivastava SC (1989) Microbial biomass acts as a source of plant nutrients in dry tropical forest and savanna. Nature 338:499–500
Singh K, Singh B, Tuli R (2013) Sodic soil reclamation potential of Jatropha curcas: a long-term study. Ecol Eng 58:434–440. https://doi.org/10.1016/j.ecoleng.2013.07.006
Singh A, Singh DP, Tiwari R, Kumar K, Singh RV, Singh S, Prasanna R, Saxena AK, Nain L (2015) Taxonomic and functional annotation of gut bacterial communities of *Eisenia foetida* and *Perionyx excavatus*. Microbiol Res 175:48–56. https://doi.org/10.1016/j.micres.2015.03.003
Sinsabaugh RL, Carreiro MM, Alvarez S (2002) Enzyme and microbial dynamics of litter decomposition. In: Burns RG, Dick RP (eds) Enzymes in the environment: activity, ecology, and applications. Marcel Dekker, Inc., New York, pp 249–265
Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)-aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res 79:7–31

Swift MJ, Heal OW, Anderson JM (1979) Decomposition in Terrestrial Ecosystems. University of California Press, Berkeley, CA, p 372

Swift MJ, Izac AMN, van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric Ecosyst Environ 104:113–134

Takimoto A, Nair VD, Nair PKR (2009) Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. Agrofor Syst 76:11–25

Tangjang S, Arunachalam A, Arunachalam K, Deb S (2015) Litterfall, decomposition and nutrient dynamics in traditional agro- forestry systems of Northeast India. Int J Ecol Environ Sci 41(1–2):43–53

Teklay T, Malmer A (2004) Decomposition of leaves from two indigenous trees of contrasting qualities under shaded coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. Soil Biol Biochem 36:777–786. https://doi.org/10.1016/j.soilbio.2003.12.013

Tian G, Kang BT, Brussaard L (1992) Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions, decomposition and nutrient release. Soil Biol Biochem 24:1051–1060

Tian G, Brussaard L, Kang BT (1993) Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions: effects on soil fauna. Soil Biol Biochem 25(6): 731–737

Tian G, Brussaard L, Kang BT (1995) Breakdown of plant residues with contrasting chemical compositions under humid tropical conditions: effects of earthworms and millipedes. Soil Biol Biochem 27(3):277–280

Tian G, Olimah JA, Adeoye GO, Kang BT (2000) Regeneration of earthworm populations in a degraded soil by natural and planted fallows under humid tropical conditions. Soil Sci Soc Am J 64:222–228

Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, Leveau JHJ, Liptzin D, Lubell M, Merel P, Michelmore R, Rosenstock T, Scow K, Six J, Williams N, Yang L (2011) Agroecology: a review from a global-change perspective. Annu Rev Environ Res 36:193–222

Udawatta RP, Kremer RJ, Adamson BW, Anderson SH (2008) Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. Appl Soil Ecol 39:153–160. https://doi.org/10.1016/j.apsoil.2007.12.002

UNESCO-SCOPE (2007) Hidden assets: biodiversity below-surface. UNESCO-SCOPE Policy Briefs No.5. UNESCO_SCOPE, Paris. 06 pages

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass carbon. Soil Biol Biochem 19:703–707

Vanlauwe B, Sanginga N, Merckx R (1997) Decomposition of four Leucaena and Senna prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. Soil Biol Biochem 29(2):131–137

Várallyay G (1989) Land evaluation in Hungary–scientific problems, practical applications. In: Bouma J, Bregt AK (eds) Land qualities in space and time, symposium organized by the International Society of Soil Science. Pudoc, Wageningen, pp 241–252

Verma N, Tarafdar JC, Srivastava KK, Panwar J (2008) Arbuscular Mycorrhizal (AM) diversity in *Prosopis cineraria* (L.) Druce under arid agroecosystems. Agric Sci China 7:754–761

Vidal A, Remusat L, Watteau F, Derenne S, Quenea K (2016) Incorporation of ^{13}C labelled shoot residues in *Lumbricus terrestris* casts: a combination of transmission electron microscopy and nanoscale secondary ion mass spectrometry. Soil Biol Biochem 93:8–16. https://doi.org/10.1016/j.soilbio.2015.10.018

Wang QJ, Bai YH, Gao HW, He J, Chen H, Chesney RC, Kuhn NJ, Li HW (2008) Soil chemical properties and microbial biomass after 16 years of no-tillage farming on the Loess Plateau, China. Geoderma 144:502–508

Wartenberg A, Blaser WJ, Gattinger A, Roshetko JM, van Noordwijk M, Six J (2017) Does shade tree diversity increase soil fertility in cocoa plantations? Agric Ecosyst Environ Appl Soil Ecol 248:190–199

Weider RK, Lang GE (1982) A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology 63(6):1636–1642

Wilson GF, Kang BT, Mulongoy J (1986) Alley cropping: trees as sources of green-manure and mulch in the tropics. Biol Agric Hon 3:251–267

Wu T, Ayres E, Bardgett RD, Wall DH, Garey JR (2011) Molecular study of worldwide distribution and diversity of soil animals. Proc Natl Acad Sci U S A 108:17720–17725. https://doi.org/10.1073/pnas.1103824108

Wu J, Zeng H, Zhao F, Chen C, Liu W, Yang B, Zhang W (2020) Recognizing the role of plant species composition in the modification of soil nutrients and water in rubber agroforestry systems. Sci Total Environ 723:138042

Yamaoh CF, Agboola AA, Wilson GF, Mulongoy K (1986) Soil properties as affected by the use of leguminous shrubs for alley cropping with maize. Agric Ecosyst Environ 18:167–177

Young A (1989) Agroforestry for Soil Conservation. CAB International, Wallingford

Zaia FC, Gama-Rodrigues AC, Gama-Rodrigues EF, Moço MKS, Fontes AG, Machado RCR, Baligar VC (2012) Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. Agrofor Syst 86(2):197–212

Zeng DH, Mao R, Chang SX, Li LJ, Yang D (2010) Carbon mineralization of tree leaf litter and crop residues from poplar-based agroforestry systems in Northeast China: a laboratory study. Appl Soil Ecol 44:133–137

Zhang D, Hui D, Luo Y, Zhou G (2008) Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J Plant Ecol 1:85–93

Zhang N, Li Y, Wubet T, Bruelheide H, Liang Y, Purahong W, Buscot F, Ma K (2018) Tree species richness and fungi in freshly fallen leaf litter: unique patterns of fungal species composition and their implications for enzymatic decomposition. Soil Biol Biochem 127:120–126

Part IV
Analytical Approaches and Policy Perspective

Chapter 17
Agroforestry Suitability Mapping: A Geospatial Approach for Quantifying Land Potential for Intensification

R. H. Rizvi, Firoz Ahmad, A. K. Handa, and A. Arunachalam

Abstract Geospatial and information technologies are now widely used in agricultural research and development, so their application in agroforestry research needs a scientific approach. Some of the applications are mapping of agroforestry areas, assessment of area under tree species on farmlands, and estimation of carbon sequestration in agroforestry systems. As far as the mapping of agroforestry areas is concerned, a single methodology may not be applicable to all types of remote sensing data. So, separate methodologies for medium- and high-resolution remote sensing data have been developed and standardized. Moreover, the identification and mapping of tree species on farmlands require more expertise than simply mapping agroforestry area and also some improved methodology. Therefore, another methodology based on object-oriented classification has been developed and successfully applied for mapping *Populus deltoides*, *Salix alba*, and *Prosopis cineraria* species.

Land suitability analysis (LSA) is a scientific method to assess the degree of fitness or suitability of land for a specific purpose. LSA and GIS are excellent tools for the sustainable planning and management of land. Agroforestry suitability mapping is also an important area, where these technologies can be judiciously applied. Land suitability for agroforestry can be done in GIS platform using different criteria like nutrient availability, slope, wetness, rainfall and elevation. Researchers have effectively utilized remote sensing and GIS modeling techniques for agroforestry suitability mapping at the local level to the national level. Geospatial and information technologies can be suitably harnessed for future agroforestry research and development in India. Both planners and farmers can be facilitated by the appropriate utilization of these technologies in decision-making.

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17.1 Introduction to Geospatial Technologies

Geospatial technologies include Remote Sensing, Geographic Information System (GIS), Global Positioning System (GPS), and Internet Mapping Technologies. These are widely used in various applications these days including in agroforestry mapping. Geospatial technologies have a huge advantage over the manual (traditional) methods of mapping because it is not only cost-effective but also executed within a limited time frame with significantly less manpower support. GIS enables the storage, management and analysis of large quantities of spatially distributed data (De Mers 1997). GIS has gained importance in land use planning and natural resource management, providing a spatial framework to aid in the decision process (Zeiler 1999). The power of GIS lies in its ability to analyze relationship between features and associated data (Samson 1995). The new generation of GIS that integrate satellite images with maps data means that this technology can be successfully used for remotely mapping and monitoring agroforestry systems. When image analysis and GIS are combined into one package; it can offer a very efficient and cost-effective solution (Buchan 1997).

Remote sensing, in the broadest sense, may be defined as a technique of acquiring information about some object or phenomenon by recording devices such as cameras, laser, radio frequency receivers, radar system, magnetometers etc. without being in physical or intimate contact with the object or phenomenon under study. Satellite images are used to identify what is growing, while GIS component is used to assess area, categorize it and locate its position on earth's surface to provide complete record of the site.

The data analysis process involves: examining the data by viewing instruments to analyze pictorial data which is called the "*Visual Image Interpretation*" techniques and by computers to analyze digital data through process known as "*Digital Image Processing*" (Fig. 17.1).

GPS technology has provided an indispensable tool for management of agriculture and natural resources. GPS is a satellite and ground-based radio navigation and locational system that enables the user to determine very accurate location on the surface of earth. By using the GPS traverse, one can directly get the nodes of the polygon, and in large traverses, the time is saved by downloading the data into computer.

Internet mapping technologies further facilitated generic users by providing software programs and applications like Google Earth, Open Street Map, and Microsoft Virtual Earth for data visualization. However, in the development of advanced internet mapping technologies, the commercial and open geospatial platforms are progressing very fast with a focus on user-friendly interface designing and geospatial data interoperable web services like WFS, WMS that are aligned to Open Geospatial Consortium (OGC) standards and guidelines.

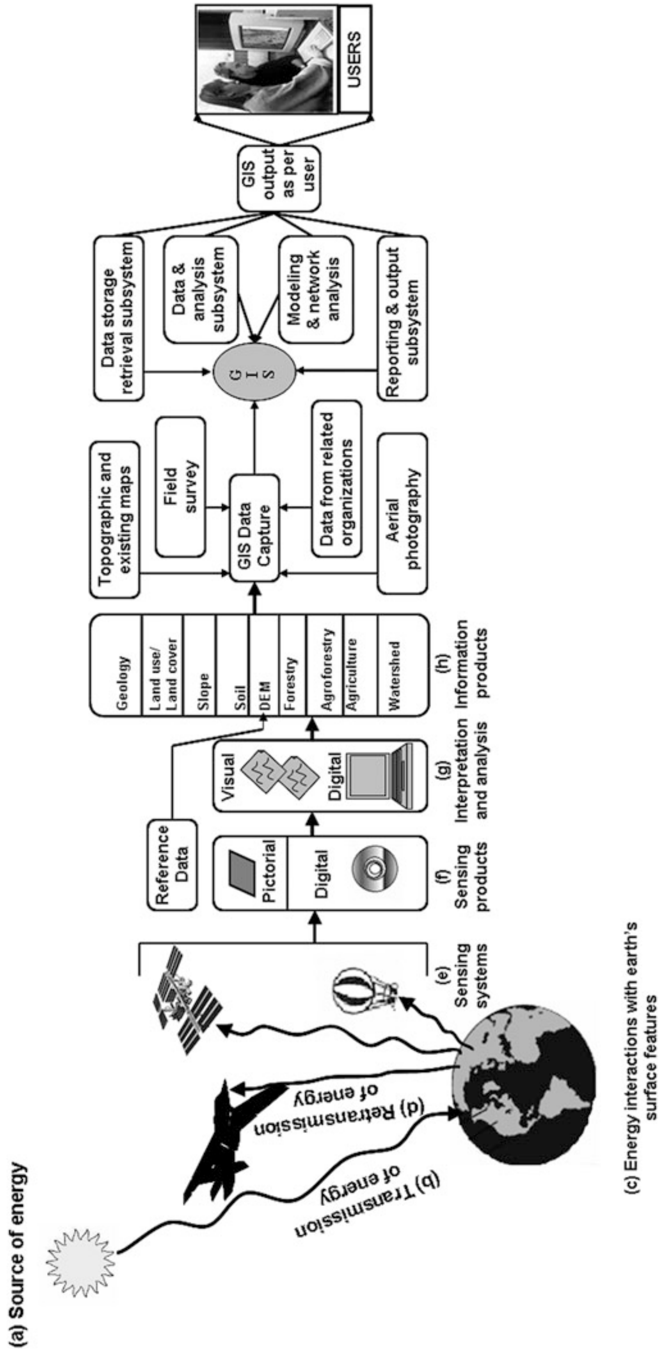


Fig. 17.1 Satellite remote sensing process integrated with GIS

17.2 Spectral Signatures and Spectral Indices

17.2.1 Spectral Signatures

Spectral signature is defined as the spectral reflectance pattern of an object or feature over electromagnetic spectrum from visible to mid-infrared spectral range. Every feature on earth (soil, vegetation, water, etc.) has different spectral reflectance pattern (signatures), by which they can be distinctly identified through remote sensing. Figure 17.2a–d depicts the spectral signatures for Neem (*Azadirachta indica*), Khejri (*Prosopis cineraria*), and Mango (*Mangifera indica*) species generated using Sentinel-2A/2B multispectral and Hyperion hyperspectral remote sensing data. Methodology developed for generation of spectral signatures using hyperspectral remote sensing data is depicted in Fig. 17.3. Spectral signatures for a tree species once generated are used for identification and mapping of that species on farmlands. *Mangifera indica* was mapped in Unnao district of Uttar Pradesh using generated signatures and Spectral Angle Mapper method (Fig. 17.4).

17.2.2 Spectral Indices

Spectral indices are some combinations of spectral bands of remote sensing data and useful in identification of physical features on earth like soil, vegetation, water, rocks, etc. Some indices are used for vegetation analysis, where some are used for soil analysis (Table 17.1).

NDVI and SARVI indices generated for Poplar plantation at different periods of time (Jan., May, and Oct.) showed that the poplar plantation was clearly identified in the May image by both NDVI and SARVI than January and October images. This is because at this time Poplar tree is full of green flesh. However, there was more clarity in SARVI image than in NDVI image (Fig. 17.5). Therefore, the selection of acquisition time of satellite data for the identification of tree species is very much important while working with different spectral indices.

17.3 Mapping of Agroforestry and Tree Species

Agroforestry mapping definition in remote sensing depends on the pixel size of the dataset used and characterized by biophysical conditions and socioecological status of the landscape (Zomer et al. 2014; Ahmad et al. 2021). Mapping tree species on farmlands need a better understanding of the spectral reflectance behavior and pattern because spectral signature significantly mixing within trees species over different spectral bands of remote sensing data. These spectral signatures both seasonal and phenological for a tree species will be useful in identification and

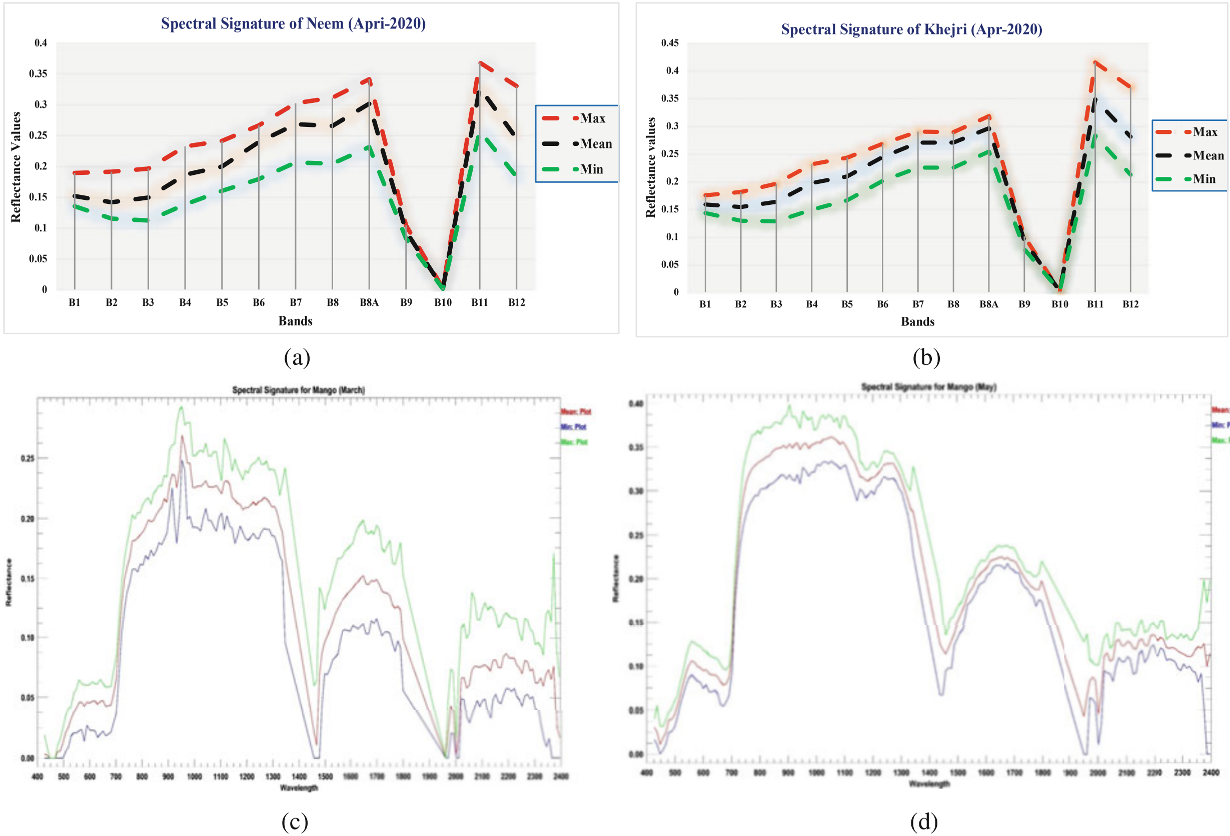


Fig. 17.2 (**a**) Spectral signatures of *Azadirachta indica* (Neem). (**b**) Spectral signatures of *Prosopis cineraria* (Khejri). (**c**) Spectral signatures of *Mangifera indica* (Mango) in March. (**d**) Spectral signatures of *Mangifera indica* (Mango) in May

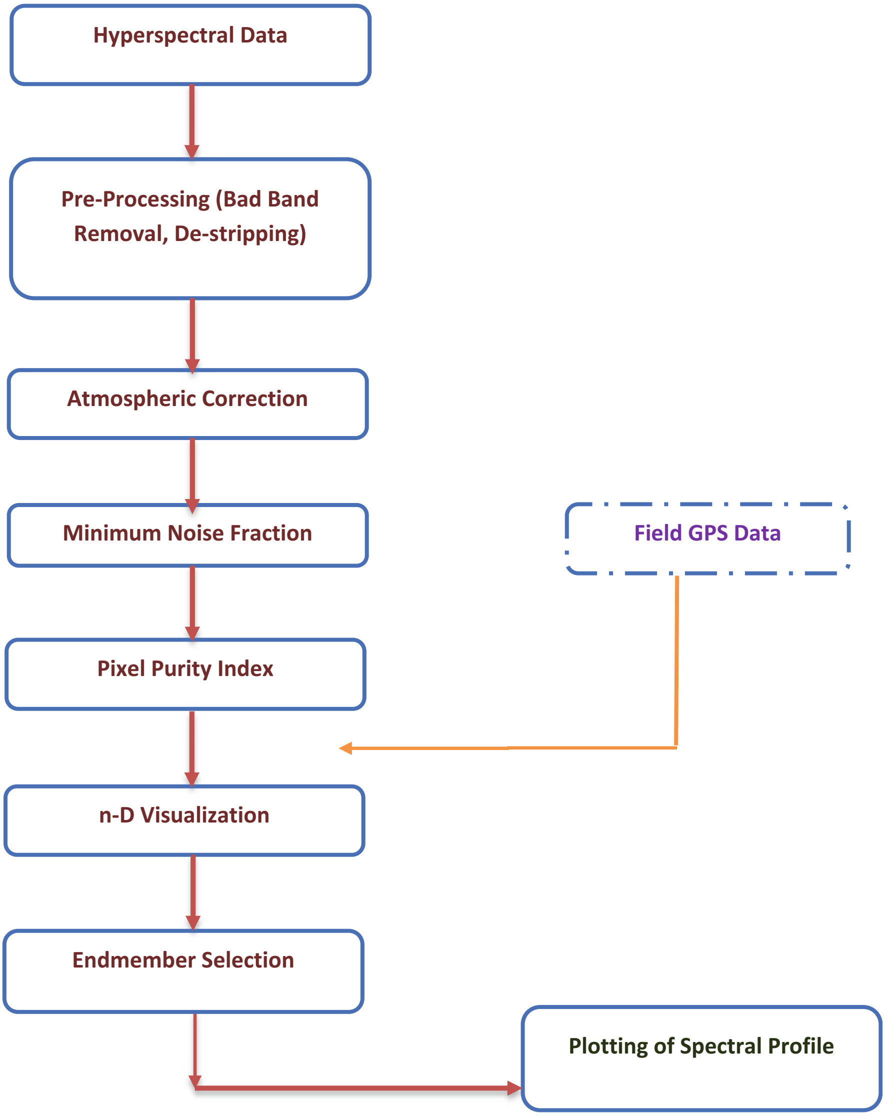


Fig. 17.3 Methodology for spectral signatures using hyperspectral remote sensing data

mapping for that particular species. For mapping tree species, multispectral remote sensing data of high spatial resolution should be used. Although attempts were made by various researchers to map tree cover/species using different remote sensing satellite data but the accuracy of mapping was significantly compromised. Rizvi et al. (2020) mapped *Populus deltoides* (Poplar) species in some districts of Punjab and Haryana (Fig. 17.6a, b) using high resolution multispectral remote sensing data (LISS-1V, spatial resolution 5.8 m) utilizing object-oriented image classification

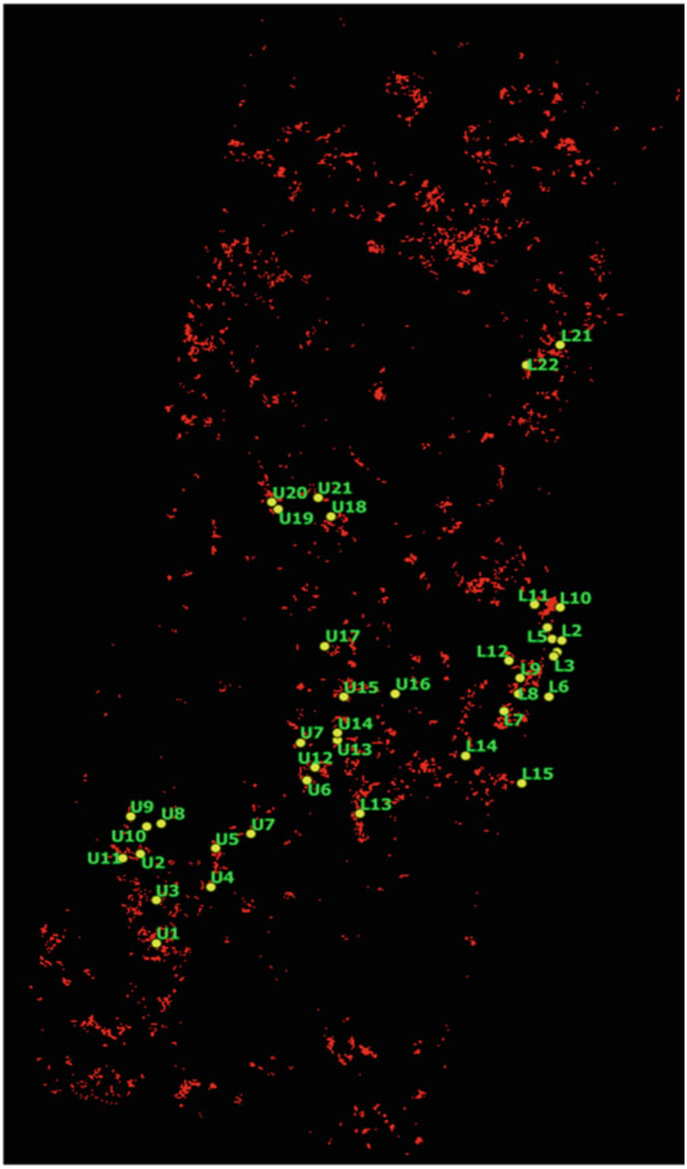


Fig. 17.4 Mapping of *Mangifera indica* shown in red color overlaid with sample points in Unnao district of Uttar Pradesh in India

method. Ahmad et al. (2021) recently used the geospatial technology and the agroforestry area of India was mapped (tree cover percent greater than 10% on agricultural land, Zomer et al. 2009) (Fig. 17.7) using remote sensing-based tree cover data for the year 2000 provided by ICRAF was found to be 28 million ha that

Table 17.1 Spectral indices used for vegetation and soil analysis

S. No.	Spectral index	Formula	Its uses/role
1.	Difference Vegetation Index (DVI)	DVI = NIR/Red	Sensitive to the amount of vegetation, distinguishes between vegetation and soil
2.	Ratio-based Vegetation index	SR = NIR/Red	High for vegetation; low for soil, water, etc. indicates amount of vegetation, reduces the effects of atmosphere
3.	Normalized Difference Vegetation Index (NDVI)	NDVI = (NIR-R)/(NIR + R)	NDVI is one of the most widely used indices for vegetation It indicates amount of vegetation, distinguishes vegetation from soil, minimizes topographic effects and is sensitive to chlorophyll
4.	Soil-Adjusted Vegetation Index (SAVI)	SAVI = [(NIR-R)/(NIR + R + L)] L is soil fudge factor that varies from 0 to 1 depending on the soil	Uses a soil background as "fudge factor"
5.	Enhanced Vegetation Index (EVI)	EVI = [(NIR-R)/NIR+ C1*R- C2*B+ L)] Where, L = 1, C1 = 6, C2 = 7.5	It enhances the vegetation signal and reduces the background noise, atmospheric noise and saturation. EVI is more responsive to canopy structural variations including leaf area index (LAI)
6.	Soil Atmospherically Resistant Vegetation Index (SARVI)	SARVI = (NIR-RB)*(1 + L)/(NIR + RB + L) Where, RB = Red-Gamma*(Blue–Red) L = 0.5 (Vegetation cover correction factor) Gamma = 1 (Aerosol content stabilization factor)	This vegetation index minimizes soil and atmospheric effects and better than NDVI
7.	Normalized Difference Salinity Index (NDSI)	NDSI = (R-NIR)/(R + NIR)	This index is mainly used for mapping different levels of soil salinity/sodicity
8.	Normalized Difference Water Index (NDWI)	NDWI = (SWIR-R)/(SWIR + R)	This index is mainly used for identification of water stress levels in vegetations

B Blue, *R* red, *NIR* near infrared, *SWIR* short wave infra-red

are approximately 17% of the total agriculture land area which is significantly less with the global average 43%. Furthermore, the study revealed that the high agricultural land potentiality (S1) toward agroforestry in India is 75.6 million ha, which is 2.7 times the total existing agroforestry extent.

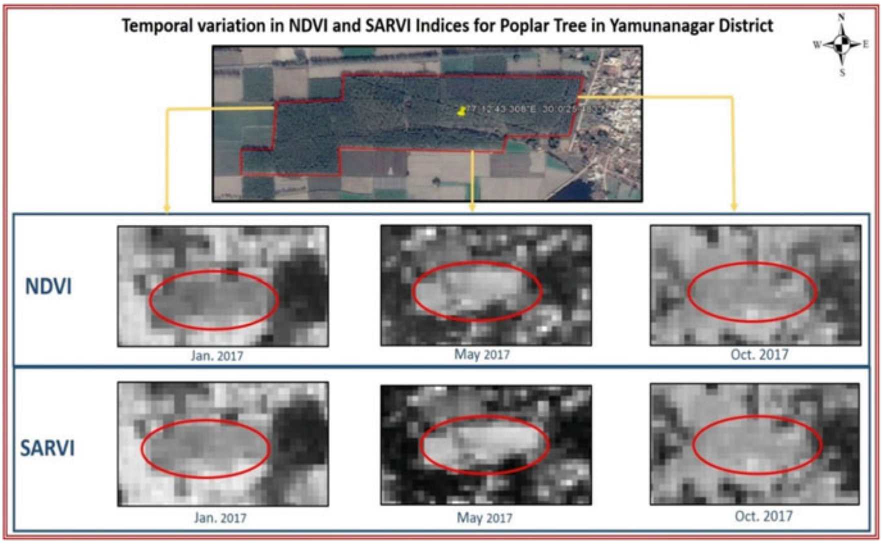
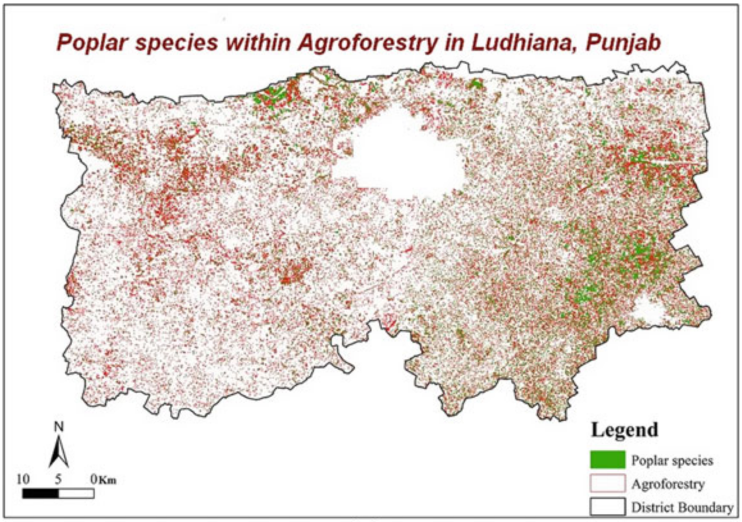


Fig. 17.5 Comparison of SARVI and NDVI indices for poplar plantation in Yamunanagar

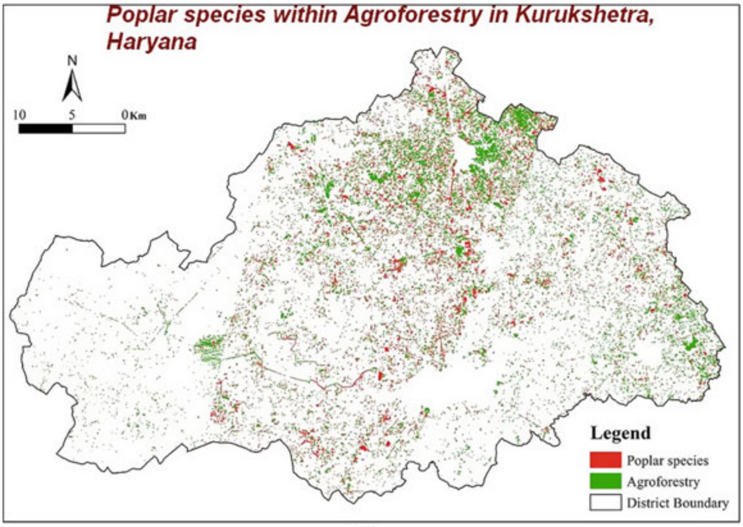
17.3.1 Agroforestry Suitability Mapping

Intensification of agroforestry environment and extending it in new areas as per land potentiality at various landscape domains can be the best approach toward achieving the Sustainable Development Goals. Land potentiality in India for agroforestry can be evaluated based on FAO land suitability criteria of utilizing various land, soil, climate and topographic themes. Land evaluation is defined as "the study of land performance/ capability when utilized for a specified purpose adequately, this includes the execution and interpretation of surveys and analysis of land forms, soils, vegetation, climate and other spatial characteristics of land in order to recognize and make a comparison of promising kinds of land use in terms of its suitability to the objectives of the evaluation" (FAO 1976). Land Suitability Analysis (LSA) is a scientific method to assess the degree of fitness or suitability of land for a specific purpose (Singha and Swain 2016; Ahmad et al. 2019). LSA and GIS are excellent tools for the sustainable planning and management of land (Collins et al. 2001; Malczewski 2004). Scientists around the globe have evaluated land potentiality in the geospatial environments for agroforestry trees (Ritung et al. 2007; Reisner et al. 2007; Joss et al. 2008; Elsheikh et al. 2013), whereas remote sensing data and GIS modeling techniques were effectively maneuvered for agroforestry suitability mapping at the local level to the national level (Ahmad et al. 2018, 2020).

The various potential themes, which is important for agroforestry plants are nutrient availability, slope, wetness, rainfall and elevation, whose weights were statistically evaluated (Table 17.2). Ahmad et al. (2019) adopted geospatial approach for agroforestry suitability mapping in India by suggesting a methodology for same



(a)



(b)

Fig. 17.6 (**a**) Poplar species mapped in Ludhiana district, Punjab. (**b**) Poplar species mapped in Kurukshetra district, Haryana

(Fig. 17.8) and estimated agroforestry suitability in broad ecosystems of India (Table 17.3). More than 40% area of subhumid, humid–subhumid, and coastal ecosystems is most suitable for agroforestry. Highest 26.9% area of arid ecosystem is not suitable for agroforestry. Ahmad et al. (2019) also estimated agroforestry suitability area of 20 agroecological regions of India by using geospatial technologies (Table 17.4). According to their estimates, 809,460 and 792,186 km^2 area is

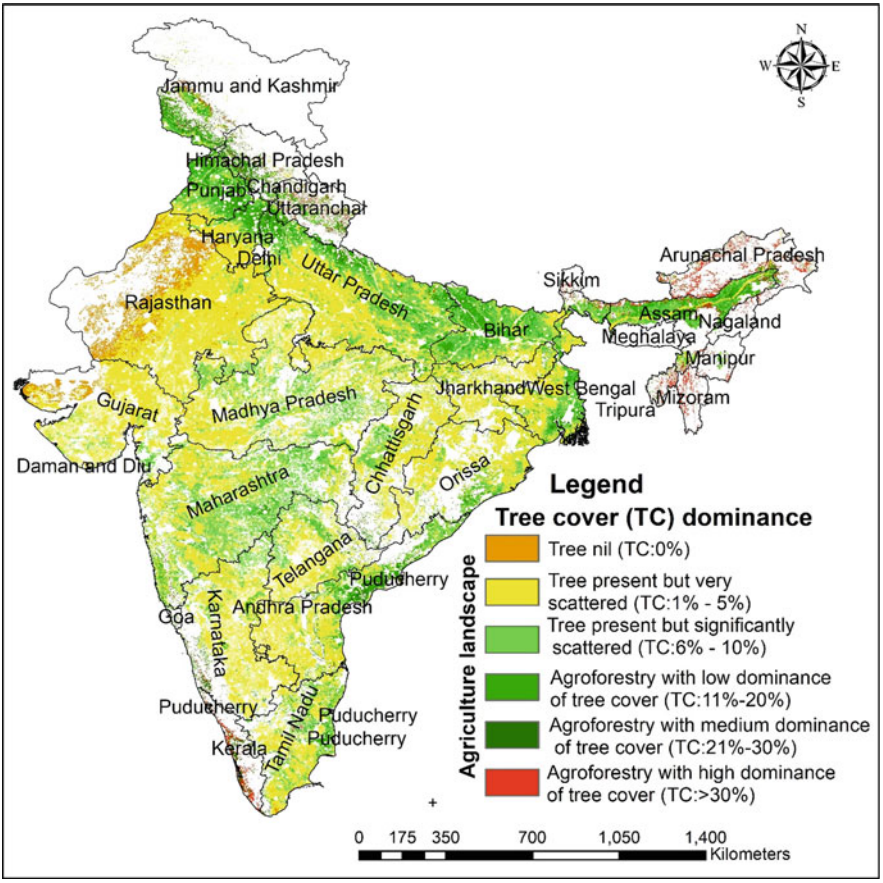


Fig. 17.7 Agroforestry extent showing tree cover dominance for the year 2000 of India. (Source: Ahmad et al. 2021)

highly suitable (S1) and moderately suitable (S2) for agroforestry out of 1,705,599 km^2 cropland area, respectively. Map showing agroforestry suitability in different agroecological regions of India is depicted in Fig. 17.9. Nath et al. (2021) evaluated the land suitability of the Eastern Indian Himalayan Region (EIHR) through multicriteria evaluation modeling through GIS. Climate, soil, topography, ecology and socioeconomic criteria having high relevance for agroforestry were analyzed and integrated to generate an agroforestry suitability map.

Table 17.2 Weight matrix of parameters for agroforestry suitability mapping

Agroforestry factor	Weightage (%)	Value/description	Rank	Suitability
Nutrient availability	35	Three categories based on weighted average output	3	High
			2	Medium
			1	Low
Slope	30	<5	3	High
		5–15	2	Medium
		>15	1	Low
Wetness factor	19	Three categories based on weighted average output	1	Low
			2	Medium
			3	High
Rainfall	10	<1000 mm	1	Low
		1000–1100 mm	2	Medium
		>1100 mm	3	High
Elevation	06	<300 m	3	High
		300–400 m	2	Medium
		>400 m	1	Low

Source: Ahmad et al. (2018)

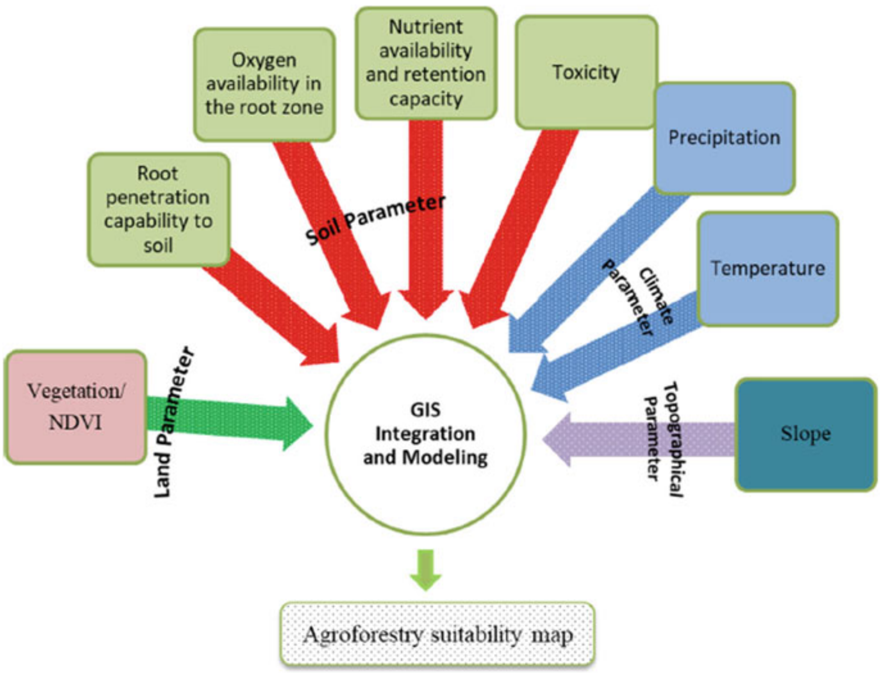


Fig. 17.8 Flowchart for agroforestry suitability mapping. (Source: Ahmad et al. 2019)

Table 17.3 Agroforestry suitability in broad ecosystems of India

Broad ecosystem	Total area (km^2)	Agroforestry suitability (%)			
		S1	S2	S3	NS
Arid ecosystem	558,662	2.8	33.5	36.7	26.9
Semiarid ecosystem	1,091,222	32.2	65.8	1.7	1.2
Subhumid ecosystem	1,096,412	56.4	28.2	10.8	4.6
Humid–perhumid ecosystem	348,324	40.1	33.7	11.5	14.6
Coastal ecosystem	185,381	60.4	20.8	0.6	18.2

Source: Ahmad et al. (2019)

17.4 Conclusions and Way Forward

There is a considerable area under agroforestry in different agroclimatic zones of India. According to an estimate by Rizvi et al. (2016, 2019), about 24.577 million ha of geographical area is occupied by agroforestry in 13 agroclimatic zones. For policy makers and planners, accurate mapping and monitoring of agroforestry are very important and challenging tasks. Geospatial technologies have excellent potential for mapping agroforestry areas and also for the estimation of standing biomass/ carbon under agroforestry systems. For mapping agroforestry environment including species more precisely, there is a strong need of developing a digital library of spectral signatures for various tree species using high-resolution remote sensing data. This would certainly help in the assessment of the contribution of agroforestry species in green tree cover and carbon sequestration.

There is an urgent need to have a Spatial Decision Support System (SDSS) for agroforestry development in India, which is aligned with the strategy of the "*National Agroforestry Policy*" of India. This SDSS would help planners and researchers in many ways in agroforestry intensification including the identification of suitable agroforestry models in various agroecological regions. Scientific use of Remote Sensing and GIS can be of great help in agroforestry extent mapping and land suitability analysis for agroforestry in various agroecological regions of India. Some of the critical evaluations of agroforestry research in India revealed the agricultural land potentiality for agroforestry is far ahead of the present agroforestry extent. Such evaluation will help in the intensification of agroforestry in a potentially suitable landscape and also boost the Government of India (GOI) targets to increase the agroforestry area up to 53 million ha by 2050. Furthermore, it will help significantly to boost the Government of India (GOI) objectives for achieving *Sustainable Development Goals*.

Table 17.4 Agroforestry suitability area in cropland of various agroecological regions of India

Agroecological region of India	Total geog. area (km^2)	Cropland area (km^2)	Agroforestry suitability area in cropland km^2			
			S1	S2	S3	NS
1. Western Himalayas (cold region)	174,162	1000	229	72	28	671
2. Western Plain and Kachchh	340,921	183,619	13,679	104,226	65,407	307
3. Deccan Plateau (hot arid)	43,579	23,741	474	22,574	391	302
4. Northern Plain & Central Highlands	326,268	278,649	149,106	128,174	1218	151
5. Central Malwa Highlands & Kathiawar Peninsula	172,101	98,225	18,203	77,085	1940	997
6. Deccan Plateau (hot semiarid region)	262,235	162,941	28,234	131,019	3372	316
7. Deccan (Telangana) Plateau & Eastern Ghats	154,548	86,933	23,798	59,232	3753	150
8. Eastern Ghats (Tamil Nadu uplands) and Deccan plateau (Karnataka)	176,070	108,255	39,494	67,197	922	642
9. Northern Plain	128,675	124,946	92,358	32,588	0	0
10. Central Highlands (Malwas & Bundelkhand)	72,351	26,508	8081	18,390	37	0
11. Deccan Plateau & Central Highlands (Bundelkhand)	149,129	69,679	34,244	35,435	0	0
12. Eastern Plateau (Chhattisgarh)	140,429	82,571	54,623	27,480	61	407
13. Eastern (Chotanagpur) Plateau & Eastern Ghats	261,243	109,307	82,707	26,334	42	224
14. Eastern Plain	123,791	112,089	97,876	14,213	0	0
15. Western Himalayas	220,793	45,171	13,275	13,711	18,007	178
16. Bengal & Assam Plains	141,115	106,850	91,689	14,539	98	524
17. Eastern Himalayas	92,500	3937	1267	1541	1022	107
18. North Eastern Hills (Purvanchal)	114,709	4764	2449	2094	221	0
19. Eastern Coastal Plain	62,811	52,375	38,290	12,262	426	1397
20. Western Ghats & Coastal Plain	122,570	24,039	19,384	4020	17	618

Source: Ahmad et al. (2019)

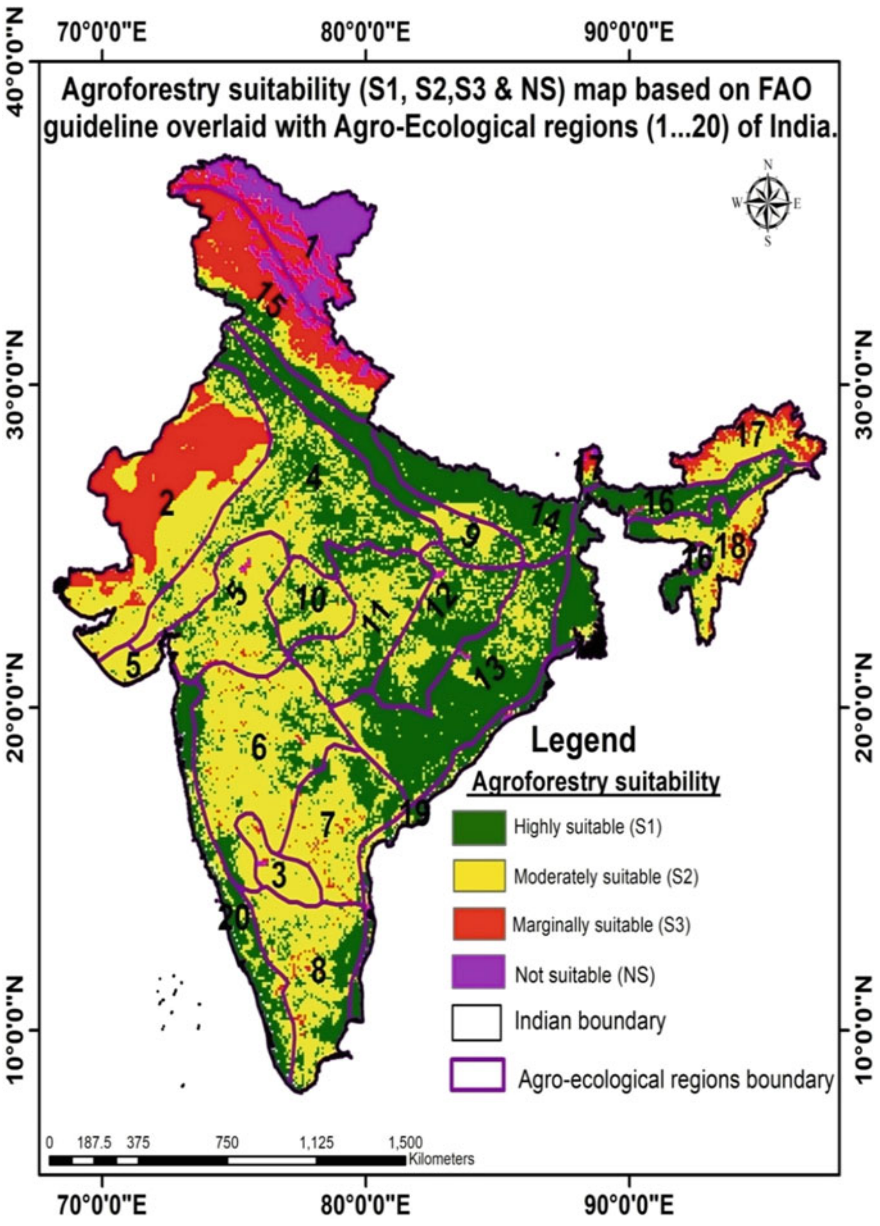


Fig. 17.9 Agroforestry suitability map of India. (Source: Ahmad et al. 2019)

References

Ahmad F, Meraj Uddin M, Goparaju L (2018) Assessment of remote sensing and GIS application in identification of land suitability for agroforestry: a case study of Samastipur, Bihar, India. Contemp Trends Geosci 7(2):214–228. https://doi.org/10.2478/ctg-2018-0015

Ahmad F, Meraj Uddin M, Goparaju L (2019) Agroforestry suitability mapping of India: geospatial approach based on FAO guidelines. Agrofor Syst 93:1319–1336

Ahmad F, Uddin MM, Goparaju L, Rizvi J, Birdar C (2020) Quantification of the land potential for scaling agroforestry in South Asia. KN J Cartogr Geogr Inf 70:71–89. https://doi.org/10.1007/s42489-020-00045-0

Ahmad F, Uddin MM, Goparaju L, Talukdar NR, Rizvi J (2021) Agroforestry environment, potentiality and risk in India: a remote sensing and GIS understanding. Environ Dev Sustain 23:15183–15203. https://doi.org/10.1007/s10668-021-01292-5

Buchan P (1997) Satellite imagery for regulatory control: modern agriculture. J Site-Specific Crop Manag 1(2):20–23

Collins M, Steiner F, Rushman M (2001) Land-use suitability analysis in the United States: historical development and promising technological achievements. Environ Manag 28(5): 611–621

De Mers MN (1997) Fundamental of geographic information systems, vol 486. Wily, New York

Elsheikh R, Mohamed Shariff ARB, Amiri F, Ahmad NB, Balasundram SK, Soom MAM (2013) Agriculture land suitability evaluator (ALSE): a decision and planning support tool for tropical and subtropical crops. Comput Electron Agric 93:98–110

FAO (1976) A framework for land evaluation. FAO Soils Bulletin 32. https://www.mpl.ird.fr/crea/taller-columbia/FAO/AGLL/pdfdocs/framele.pdf

Joss BN, Hall RJ, Sidders DM (2008) Fuzzy-logic modeling of land suitability for hybrid poplar across the Prairie Provinces of Canada. Environ Monit Assess 141:79–96

Malczewski J (2004) GIS-based land-use suitability analysis: a critical overview. Prog Plann 62(1): 3–65

Nath A, Kumar R, Devi N, Rocky P, Uttam KG, Rai KS, Bajpai K, Sahu N, Pandey R (2021) Agroforestry land suitability analysis in the Eastern Indian Himalayan region. Environ Chall 4: 100199. https://doi.org/10.1016/j.envc.2021.100199

Reisner Y, de Filippi R, Herzog F, Palma JHN (2007) Target regions for silvoarable agroforestry in Europe. Ecol Eng 29:401–418

Ritung S, Wahyunto Agus F, Hidayat H (2007) Land suitability evaluation with a case map of Aceh Barat district, Indonesian Soil Research Institute and World Agroforestry Centre, Bogor. ISBN: 979-3198-36-1

Rizvi RH, Newaj R, Karmakar PS, Saxena A, Dhyani SK (2016) Remote sensing analysis of agroforestry in Bathinda and Patiala districts of Punjab using sub-pixel method and medium resolution data. J Indian Soc Remote Sens 44(4):657–664

Rizvi RH, Newaj R, Handa AK, Sridhar KB, Kumar A (2019) Agroforestry mapping in India through Geospatial technologies: present status and way forward. Technical Bulletin-1/2019, ICAR- CAFRI, Jhansi, pp 1–35

Rizvi RH, Sridhar KB, Handa AK, Singh RK, Dhyani SK, Rizvi J, Dongre G (2020) Spatial analysis of area and carbon stocks under *Populus deltoids* based agroforestry systems in Punjab and Haryana states of indo-Gangetic plains. Agrofor Syst 94(6):2185–2197

Samson SA (1995) Determining need for a geographic information system (GIS). J Ext 33(5) http://www.joe.org/joe/1995october/tt2.html

Singha C, Swain KC (2016) Land suitability evaluation criteria for agricultural crop selection: a review. Agric Rev 2016(37):125–132

Zeiler M (1999) Modeling our world: the ESRI guide to geodatabase design. ESRI Press, Redland, CA, p 19

Zomer RJ, Trabucco A, Coe R, Place F (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper no. 89. Nairobi, Kenya

Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. Working Paper no. 179. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Bogor. https://doi.org/10.5716/WP14064.pdf

Chapter 18
Agroforestry as a Climate-Smart Agriculture: Strategic Interventions, Current Practices and Policies

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Abstract Global climate projections present a very grim picture for the future of agriculture in parts of Africa and Asia. Projections indicate marked impact on rainfall patterns and the mean annual temperature variations in both Africa and Asia. Climate change will be affecting crop yields, food security and livelihood of people. Therefore, there is an urgent need for adoption of climate-smart agricultural practices to achieve sustainable increase in production, adaptation and mitigating climate change. This chapter aimed to provide a synthesis of the state of knowledge and the evidence for the role of agroforestry in achieving the triple objectives of increasing production, improving resilience and mitigating climate change. Through literature review, we first identified and established appropriate indicators and metrics for assessing achievement of these objectives. We also explored the evidence for the potential of different agroforestry practices to provide the productivity, adaptation and mitigation benefits. We concluded that evidence abounds for the different agroforestry practices to provide productivity, adaptation and mitigation benefits. However, enabling policies and incentive mechanisms are needed to address many of the challenges that underpin the low investment in agroforestry as a climate-smart agricultural practice.

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18.1 Introduction

Climate change is widespread, rapid and intensifying, and many changes are now irreversible according to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC 2021). Concentrations of greenhouse gases have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO_2), 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019. Land and oceans have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with some regional differences. Global surface temperature in the first two decades of the twenty-first century (2001–2020) was 0.99 °C higher than 1850–1900 and the same was 1.09 °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 °C) than over the ocean (0.88 °C). The estimated increase in global surface temperature since the Fifth Assessment Report (AR5) is principally due to further warming by +0.19 °C since 2003–2012 (IPCC 2021). It is likely that human influence contributed to the pattern of observed temperature and precipitation changes since the mid-twentieth century. Further, the report shows a 1.5 °C warming (IPCC 2021). Climate projections also paint a dire picture for the future in Africa and Asia. Heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia and more frequent and severe agricultural and ecological droughts are projected especially in Africa (IPCC 2021).

According to the Coupled Model Intercomparison Project Phase 5 (CMIP5), which are the latest General circulation models (GCMs), with the current emissions trajectory temperatures in Africa will increase by up to 1.7 °C, 2.7 °C and 4.5 °C by the 2030s, 2050s and 2080s, respectively (Girvetz et al. 2019). While future precipitation is much more difficult to model, the median of the CMIP5 models indicates that by 2050, under the higher emission scenario, annual precipitation will increase across much of eastern and central Africa, while decreasing across parts of southern, western and northern Africa (Girvetz et al. 2019). Similarly, parts of Asia will experience an increase in temperatures up to 1.6 °C, 2.6 °C and 5.5 °C by the 2030s, 2050s and 2080s, respectively (Lee et al. 2020).

Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual precipitation over the past century (Hijioka et al. 2014). Precipitation trends, including extremes, are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia. In northern Asia, the observations indicate some increasing trends of heavy precipitation events, but in central Asia, no spatially coherent trends were found. Both the East Asian summer and winter monsoon circulations have experienced an inter-decadal scale weakening after the 1970s, due to natural variability of the coupled climate system, leading to enhanced mean and extreme precipitation along the Yangtze River valley (30°N), but deficient mean precipitation in North China in summer. A weakening of the East Asian summer monsoon since the 1920s was also found in sea level pressure gradients. In West Asia, a weak but non-significant downward trend in mean precipitation was observed in recent decades, although with an increase in intense weather events.

In South Asia, seasonal mean rainfall shows inter-decadal variability, noticeably a declining trend with more frequent deficit monsoons under regional inhomogeneities. Over India, the increase in the number of monsoon break days and the decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean rainfall but an increase in extreme rainfall events occurred at the expense of weaker rainfall events over the central Indian region and in many other areas. In South Asia, the frequency of heavy precipitation events is increasing, while light rain events are decreasing. In Southeast Asia, annual total wet-day rainfall has increased by 22 mm per decade, while rainfall from extreme rain days has increased by 10 mm per decade, but climate variability and trends differ vastly across the region and between seasons. In Southeast Asia, between 1955 and 2005 the ratio of rainfall in the wet to the dry seasons increased. While an increasing frequency of extreme events has been reported in the northern parts of Southeast Asia, decreasing trends in such events are reported in Myanmar. In Peninsular Malaya during the southwest monsoon season, total rainfall and the frequency of wet days decreased, but rainfall intensity increased in much of the region. On the other hand, during the northeast monsoon, total rainfall, the frequency of extreme rainfall events, and rainfall intensity all increased over the peninsula.

In Southeast Asia, annual mean surface temperature will likely increase by a slightly smaller amount than the global average. East Asian Monsoon precipitation has changed, with drying in the north and wetting in the south since the 1950s, and annual mean precipitation totals have increased over most territories of North Asia since the mid-1970s. South Asian summer monsoon precipitation decreased over several areas since the mid-twentieth century but is likely to increase during the twenty-first century, with enhanced interannual variability (IPCC 2021). In South Asia, a 0.5–1.2 °C rise in temperature is projected by 2020, 0.88–3.16 °C by 2050 and 1.56–5.44 °C by 2080, with the variation depending on the scenario of future development (IPCC 2007a, b, c). Overall, the temperature increases are likely to be much higher in the winter season than in the rainy season, while precipitation is likely to increase in all time scales in all the months except during December–February when it is likely to decrease (FCCC 2012). Increases in precipitation and rivers floods are projected over much of Asia. Aridity in East and West Central Asia is projected to increase, especially beyond the middle of the twenty-first century and global warming levels beyond 2 °C. Over East Asia, historical trends of annual precipitation show considerable regional differences but with increases over northwest China and South Korea. Extreme hydrological drought frequency will increase in a region extending from southwest to northeast China, with projected increases of agricultural and ecological drought for 4 °C GWL and fire weather for 2 °C and above. Over North Asia, annual mean precipitation totals have very likely increased, causing more intense flooding events, and the number of dry days has decreased. Concurrently total soil moisture is projected to decline extensively. Over Southwest Asia, an observed annual precipitation declined over the Arabian Peninsula since the 1980s of 6.3 mm per decade is contrasted with observed increases between 1.3 mm and 4.8 mm per decade during 1960–2013 over the elevated part of eastern West Central Asia, along with an increase of the frequency and intensity of extreme precipitation (IPCC 2021).

McKinsey Global Institute (2020) described trends of climate change in Asia identifying four regions (Frontier Asia, Emerging Asia, Advanced Asia, and China) each with a different climate profile and exposure and response to physical climate risk. Frontier Asia consisting of Bangladesh, India, and Pakistan could see extreme increases in heat and humidity and by 2050, their average temperatures are projected to rise by two to four degrees Celsius, and they could face much higher probabilities of lethal heat waves and could see extreme precipitation events more frequently than in the second half of the twentieth century and may experience less drought. Climate change would also have the biggest negative impact on crop yield in this group of countries. The countries of Emerging Asia (consisting of Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam), are projected to see extreme increases in heat and humidity by 2050 (although potentially less extreme than in Frontier Asia), and growing exposure to extreme precipitation events. Advanced countries in Asia (e.g. Japan and South Korea) are expected to see slightly lower impacts of climate change along many dimensions than Frontier Asia and Emerging Asia. Rather, these countries along with Australia and New Zealand are expected to be an agricultural net beneficiary of climate change in the near term. However, for some countries in the region, the effects on water supply and drought are the main challenges. Typhoon and extreme precipitation risk could also increase in some parts of Japan and South Korea. China is climatically heterogeneous due to its location on a wide range of latitudes. Still, the country in aggregate is predicted to become hotter. Like Advanced Asia, China is expected to be an agricultural net beneficiary of climate change in the near term, with increasing statistically expected yields and volatility skewed towards positive outcomes. However, risk of more frequent extreme precipitation events and typhoons in many areas will remain. These changes in temperature and precipitation will have significant implications for agriculture. In Africa, current growing areas of maize and beans are projected to experience 12–40% yield reductions by the 2050s (Girvetz et al. 2019). Much of agriculture's vulnerability to climate change lies in the fact that agriculture remain largely rain-fed in Africa (Girvetz et al. 2019) and parts of Asia (Barker and Molle 2004). It is projected that in Asia climate change will affect food security by the middle of the twenty-first century, with the largest numbers of food-insecure people located in South Asia. Most simulation models show that higher temperatures will lead to lower rice yields as a result of a shorter growing period (Hijioka et al. 2014).

Climate-smart agriculture (CSA) (as defined by FAO 2013) aims to achieve three goals simultaneously: sustainably increasing production, improving resilience and mitigating climate change (Campbell et al. 2014; Vermeulen 2019). As such, CSA practices are presumed to enhance synergies between the productivity, resilience, and mitigation objectives. CSA presupposes the integration of climate change into sustainable agriculture planning and implementation at a local scale (Campbell et al. 2014). Hundreds of technological solutions have been identified as climate-smart

(FAO 2013; Vermeulen 2019). Many agroforestry practices can be CSA practices, and much research has been on-going to assess their potential for increasing productivity, adaptive capacity and mitigating emissions from agriculture across Africa and Asia (Chatterjee et al. 2018; Das et al. 2022; Kuyah et al. 2019; Lorenz and Lal 2014; Muchane et al. 2020; Nath et al. 2021; Shi et al. 2018; Sileshi et al. 2008, 2011). Our objective in this chapter is to provide a synthesis of the state of knowledge and the evidence for the role of agroforestry in achieving the triple objectives of increasing production, improving resilience, and mitigating climate change. First, we will identify and establish appropriate indicators and metrics. Then, we will review the literature and provide the evidence for the potential of the different agroforestry practices to provide the benefits.

18.2 Indicators and Metrics for Climate Smartness of Agroforestry

The productivity, adaption and mitigating benefits of agroforestry can be fully understood, communicated by practitioners and appreciated by decision-makers when appropriate indicators and metrics are used. Indicators are often used to describe, represent, monitor, assess or model complex world processes, components or properties, both qualitatively and quantitatively, to be used in decision-making processes (Heink and Kowarik 2010; Mafongoya and Sileshi 2020). ‘Indicator’ is defined here as a sign of the presence or absence of the concept being measured. A metric is a specific property of a farming system, cropping system, a biotic community or household that can be directly measured (Mafongoya and Sileshi 2020). The multiplicity of benefits from agroforestry means that several complementary and meaningful indicators and metrics need to be used. However, these are not clearly defined and systematically applied. Therefore, in this section, we will identify and define relevant indicators and metrics based on the published literature (Table 18.1).

Here, we suggest using a collection of metrics to characterize and compare productivity, adaptation and mitigation metrics. According to Aldy and Pizer (2015) metrics should be comprehensive, measurable, and universal. An ideal metric should be comprehensive, characterizing the effort actively undertaken by a country to achieve its mitigation commitment. It should take on similar values for countries undertaking similar mitigation efforts. A metric should also be measurable and replicable. The ability to replicate a given metric without subjective assumptions, using available public information, enhances the credibility of the information. Metrics should be universal. Given the global nature of the climate change challenge, metrics should be constructed for and applicable to as broad a set of countries as possible (Aldy and Pizer 2015). The relevant indicators and metrics of productivity, adaptation and mitigation have been summarized in Table 18.1.

Table 18.1 Summary of indicators and metrics

Group/class	Indicators	Metrics
Productivity	Yields of food crops	Increase relative to 'no-tree' plot
	Milk, meat, eggs, honey yield	Increase relative to 'no-tree' plot
	Yields of feed crops (Mg ha^{-1})	Increase relative to 'no-tree' plot
	Yields of fibre crops (Mg ha^{-1})	Increase relative to 'no-tree' plot
	Yields of energy crops (Mg ha^{-1})	Increase relative to 'no-tree' plot
	Biofuel, biodiesel, bioethanol (EJ $year^{-1}$)	Increase relative to 'no-tree' plot
	Energy from manure (EJ $year^{-1}$)	Increase relative to 'no-tree' plot
Adaptation	Soil hardiness	Decrease relative to 'no-tree' plot
	Aggregate stability	Increase relative to 'no-tree' plot
	Water use efficiency / water productivity	Increase relative to 'no-tree' plot
	Effective rooting depth	Increase relative to 'no-tree' plot
	Soil pH	Increase relative to 'no-tree' plot
	Cation exchange capacity (CEC)	Increase relative to 'no-tree' plot
	Nutrient availability	Increase relative to 'no-tree' plot
	Electrical conductivity	Increase relative to 'no-tree' plot
	Soil organic carbon content	Increase relative to 'no-tree' plot
	Active carbon	Increase relative to 'no-tree' plot
	Soil protein	Increase relative to 'no-tree' plot
	Soil respiration rate	Increase relative to 'no-tree' plot
	Agricultural income ($, $$ha^{-1}$)	Increase relative to 'no-tree' plot
Mitigation	Biomass carbon (Mg ha^{-1})	Increase relative to 'no-tree' plot
	SOC in cropland (Mg ha^{-1})	Increase relative to 'no-tree' plot
	SOC in rangeland (Mg ha^{-1})	Increase relative to 'no-tree' plot
	Humidity index	Increase relative to 'no-tree' plot
	Soil cover (%)	Increase relative to 'no-tree' plot
	Erosion rate (Mg ha^{-1} $year^{-1}$)	Decrease relative to 'no-tree' plot

18.2.1 Productivity Indicators and Metrics

Trees within farmers' fields can enhance systems' longer-term productivity, for example, via nutrient amelioration (Dierks et al. 2021) and provision of livestock feed. In cropping systems, yield defined as the production of crops per unit of land area is a key metric of productivity. This can be measured either in kg ha^{-1} grain (Rai et al. 2009) or as value of crop produced ($ ha^{-1}). In livestock systems, yield can be measured as the production of animal products (milk, meat or eggs) per livestock unit per day, or the production of milk per animal per lactation period (van Zanten et al. 2016). In agroforestry systems, crop yields are often used as the main metrics of productivity (Leakey 2010). Crop yield can also be used as a proxy for food availability (Leroux et al. 2022). Yields of agricultural by-products may be used as metrics of availability of animal feed (Table 18.1). Value-added agroforestry products may enhance the system productivity in terms of nutrition and livelihood security by enhancing the income of different stakeholders. Installation of product-based industry in areas of dominance of a particular crop in a region may open new opportunities of enhancing diverse agroforestry products.

18.2.2 Adaptation Indicators and Metrics

The adaptation benefits of agroforestry include maintenance of soil quality (Muchane et al. 2020), microclimate modulation, more efficient use of water and nutrients, reduced risks of crop failure and income diversification. Soil quality affects not only agricultural productivity, but it is also a significant factor governing environmental quality, human and animal health. Arora and Dagar (2019) reported salinity tolerant indicators. A salinity indicator is that symptom which reflects the impacts of soil salinity. The physical indicators of salt-affected soils include flocculation, dispersion of clays and surface salt crusts, infiltration rate, hydraulic conductivity; and conventional chemical indicators of soil salinity include electrical conductivity (EC), pH, total dissolved solids (TDS), exchangeable sodium percentage (ESP), electrochemical stability index (ESI), and sodium adsorption ratio (SAR). Plant species that serve as indicator (halophyte) can be commonly used in combination with physical and chemical and biological (dehydrogenase activities governed by microbial population) indicators to determine soil salinity and may contribute in evolving adaptation technologies. Mafongoya and Sileshi (2020) have reviewed and synthesized the various indicators of soil health reported in the literature. Indicators of soil health are intimately related to the physical, chemical and biological properties of the soil, which play a key role in adaptation. The main indicators of soil physical quality include soil hardness, aggregate stability, available water capacity, infiltration rate and effective rooting depth. Relevant indicators of soil chemical quality include pH, CEC, carbon to nitrogen ratio (C/N), carbon and nitrogen mineralization rates, nutrient availability, electrical conductivity, salinity, sodicity, toxicity or deficiency (Lal 2015a). The biological indicators include soil organic matter (SOM), active carbon, soil protein, soil respiration, and the abundance and diversity of soil fauna and flora (Mafongoya and Sileshi 2020). SOM or the soil organic carbon (SOC) pool is the most reliable indicator of monitoring soil degradation (Lal 2015a). Trees help to achieve soil health benefits through increases in SOM, control of soil erosion and increased soil biological activity (Barrios et al. 2012; Sileshi et al. 2014a, b). Agroforestry trees enhance SOM both through production of SOM and reducing losses due to erosion. In arid regions in western India, Soni et al. (2008) reported significantly higher SOC in agroforestry systems as compared to traditional cropping system. Significantly higher SOC was recorded in upper soil layers of 0–10 cm. The increase in SOC was recorded from 0.09% in traditional cropping system to a maximum of 0.39% in agroforestry systems (Soni et al. 2008).

Water use efficiency is another key indicator rarely used in the agroforestry literature. In rain-fed agriculture, water use efficiency is linked to the effectiveness of the use of precipitation received during the cropping season (Hatfield et al. 2001).

Therefore, rain use efficiency (RUE) defined as the ratio of aboveground net primary production (ANPP) to annual rainfall provides information similar to water use efficiency (Sileshi et al. 2011). RUE is known to provide a sensitive metric for evaluating ecosystem resilience (Huxman et al. 2004). Agroforestry practices can increase the efficiency with which rainfall and moisture available in the soil are used (Sileshi et al. 2011) thus reducing climate related risks of water stress on crops.

Water productivity in cropping system plays a crucial role in modern agriculture which aims to increase production per unit of water used, both under rain-fed and irrigated conditions. It is expressed as crop production per unit volume of water and can be expressed as kg m^{-3}. Agroforestry system can increase water productivity (Soni et al. 2017): (1) Understory vegetation comprising C_3 plants, e.g., cotton and C_3 grasses, which shows better water productivity as compared to C_4 species; (2) tree shade increases humidity of understory vegetation in semiarid climates, e.g., parkland systems and windbreaks; (3) planting of trees as contour hedgerows on hill slopes increases infiltration and reduces runoff; (4) presence of deep water beyond the reach of crop rooting systems, trees like *Prosopis cineraria* have capacity to absorb moisture from deeper soil layer; (5) trees can use rains that fall outside the cropping season; and (6) trees have canopy architecture that intercepts high amounts of water per unit shade. There are substantial experimental evidences to support the hypothesis that agroforestry may increase productivity by making better use of available resources. Ong et al. (1992) reported that widely spaced alley crops (4 m × 4 m between hedges) extracted more water than sole *Leucaena leucocephala*, indicating that the agroforestry system was most effective in exploiting available water. Similarly, Ong et al. (1996) observed substantial improvements in productivity resulting from increased utilization of annual rainfall from 40% to 80% in agroforestry systems containing perennial pigeon pea (*Cajanus cajan*) and groundnut (*Arachis hypogaea*). Almost half of the annual water use (416 mm versus 887 mm) occurred between January and June, when only 211 mm of rainfall, indicating that 205 mm was extracted from soil reserves. Droppelmann et al. (2000) and Ong et al. (2000) reported that the yield of intercrop (sorghum) in combinations with pruned trees was similar to their yields when grown as monocrops. This shows that there can be complementarities in resource use between different agroforestry system components.

In arid regions due to hot windy weather, the rate of loss of water through transpiration can be very high and can result in early depletion of limited soil moisture reserves. This in turn can lead to serious water-stresses developing in crops before their cycle of growth to maturity is completed. Windbreaks significantly reduce wind speed and so reduce crop transpiration rates and the unnecessary loss of soil water. These are usually established by planting single, double or triple rows of trees or bushes. Well-designed windbreaks can significantly reduce evapotranspiration rates of crops in windy conditions resulting in the conservation of soil water and less subsequent moisture stress when water is limiting. Windbreaks may provide additional benefits to crops by reducing mechanical damage and the loss of flowers and by creating better conditions for insect pollination. They are also beneficial in reducing wind erosion, especially in fine sandy and silty soils, and in diminishing air pollution problems.

The tree canopies in agroforestry systems intercept the rain and reduce runoff. Trees create a unique microenvironment around them by positively modifying their underneath soil physicochemical and biological properties and by direct influence on sunlight and atmospheric conditions. Transpiration and canopy are the main factors affecting air temperature, humidity. Wind speed, quantity and quality of light and soil temperature, photosynthetic pathway and phenology of the understory crop, pH, decrease saturation deficit and evaporative demand of crops, moisture and nutrient availability (Monteith et al. 1991; Zemmrich et al. 2010). So, there is the potential for microclimate modification in agroforestry systems, due to the presence of an elevated tree canopy. This may alter not only the radiation but also the humidity and temperature around an understory crop. Gain in total biomass production can be achieved when modification of the microclimate by trees increases the water-use-efficiency of the crop (Livesley et al. 2004). The improved micro-environmental conditions beneath savannah trees favour soil biotic activity, nutrient transformations and improved physical conditions. Coleman et al. (1991) and Kaur et al. (2002b) measured higher soil microbial biomass, greater numbers of microbivorous nematodes and larger amounts of mineralizable N beneath savannah tree canopies and in silvopasture on degraded sodic soils. Belsky (1994) found higher rates of N mineralization beneath both *Adansonia digitata* and *Acacia tortilis* associated with lower bulk density and higher water infiltration. Shading decreased the mean diurnal temperature range and maximum meristem temperature by up to 7 °C relative to monocrop maize in *Grevillea robusta*-based agroforestry systems in semiarid Kenya (Ong et al. 2000). Kohli and Saini (2003) reported that microclimatic conditions under agroforestry were more favourable for wheat seed germination, growth attributed to reduction in heat load during the post-anthesis period.

Soni et al. (2017) reported that trees in agroforestry play important role in capturing nutrients leached from the topsoil, and they can return these to the soil surface as litter and rates of N accumulation of 43–581 kg N ha^{-1} $year^{-1}$ was reported in several tropical plantation trees, even though not all N originated directly from the atmosphere. However, several important tree species, including some *Acacia* and *Vachellia* species, have been shown to accumulate N at very low rates (<50 kg N ha^{-1} $year^{-1}$). Some nitrogen fixing trees like *Cassia senna* increase nutrient availability to crops (Duarte et al. 2013). It is well established fact that crop yields in association with *Prosopis juliflora* and *Faidherbia albida* is higher than when cultivated in isolation. Trees can access nutrients from sub-soil that are not accessible to shallower rooted plants, including nutrients leached through surface soil (Rowe et al. 1998). These nutrients can subsequently become available to annual plants through above and below-ground litter production. This nutritional benefit to crops is delivered slowly, depending on the speed of litter decomposition and nutrient supply. The release of nutrients is species specific. In fruit-based cropping systems, Soni et al. (2013a, b) reported faster release of nitrogen from the litter in *Citrus aurantifolia* and *Aegle marmelos* and making it available for crops. The N release by the litter of *Cordia myxa* was very slow and could be ascribed to its slow decomposition due to higher lignin content (45.8%) as compared to *C. aurantifolia* (19.8%) and *A. marmelos* (15.3%).

Competition for light is another important consideration between trees and crops in agroforestry systems. Trees reduce the amount of sunlight reaching soils and crops through shading. Light capture is influenced by both environmental (Temperature, wind, cloud situation, humidity, etc.) and plant factors such as tree leaf area, leafing phenology, crown structure and crown management. Unless trees are leafless during the cropping season or heavily pruned, competition is substantial. For example, under *Faidherbia albida*, which sometimes exhibits 'reverse phenology' by shedding leaves at the beginning of the rainy season and foliating in the dry season, light interception is generally considered to be low and not to affect crop production significantly (Boffa 1999). Similarly, *Populus deltoides* sheds its leaves during winter and there is no shade effect on wheat or mustard crops in Indo-Gangetic plains and the yield of rice during *kharif* season is not affected much due to foliage. Light competition, of course, is of little importance in rotational or segregated agroforestry systems, where trees and crops do not occur in the same space at the same time. Competition for light has been comprehensively studied in a wide range of tropical and temperate agroforestry systems and general models developed at various levels of spatial and temporal disaggregation (Charbonnier et al. 2013).

Sridhar and Bagyaraj (2017) reviewed the role of microbial biodiversity in agroforestry systems which include symbiotic and non-symbiotic nitrogen fixing bacteria, mutualistic fungi and their influence on productivity of agroforestry systems. Roy et al. (2017a, b) have given an interesting account on biodiversity of micro-arthropods and role of entomology in sustaining agroforestry productivity, the area which has not been explored much in agroforestry research.

Yield variability indexed by the coefficient of variation can also be used as an indicator of risk and resilience.

Several studies have shown how the uptake of agroforestry has helped farmers increase income from agriculture. For example, our work in Malawi (Coulibaly et al. 2015) has demonstrated that better access to agroforestry technologies create income opportunities thus improving households' adaptive capacities. Smallholder farmers who embrace agroforestry have a diversified income through improved maize yields, and the sale of some agroforestry by-products such as fuel wood. In a study conducted in Malawi by Quinion et al. (2010), fertilizer tree technologies or soil fertility improving trees increase crop production and provide additional income to households through sources such as sale of agroforestry tree seed and fuel wood. According to Simelton et al. (2015), trees on farms can help the farmers reduce the economic recovery time after natural disasters. Molua (2005) indicated three ways in which agroforestry increase farm profitability, through improvement and diversification of output per unit area of tree/crop/livestock; through protection against damaging effects of wind or water flow, and finally, through new products added to the financial diversity and flexibility of the farming enterprise. All these lead to increased agricultural and household incomes by the farmers embracing agroforestry which serve as an adaptation measure. Similarly, there is evidence that trees on-farm can provide wild edible fruits and non-timber products that serve as alternative food during periods of deficit and serve as primary sources of income for many rural communities (Assogbadjo et al. 2012). Kuntashula and Mungatana (2013) concluded that the uptake of the agroforestry improved fallow system by Zambian farmers significantly increased incomes from a unit area of the staple maize crop. In a recent study by Nkhuwa et al. (2020), farmers embracing improved fallow systems in Eastern Zambia increased their household incomes by 48–67%.

18.2.3 Mitigation Indicators and Metrics

Agroforestry systems are said to have higher attainable mitigation potential than other practices such as grain legume rotations, manure application and minimum tillage applied on farmland (FAO 2015). Among agricultural mitigation options, carbon (C) storage in biomass and soil C sequestration is one of the few strategies that could be applied at large scales and with lower cost (Paustian et al. 2016). In that sense, amounts of biomass C and SOC stored in agroforestry systems (given in CO_2 equivalents) are relevant indicators.

SOC is now well-established as the key indicator of sequestration following the 21st Conference of Parties (COP21). The '4 per mille' aspiration proposed during COP21 was aimed at making agriculture a solution to address climate change while also advancing food and nutritional security (Minasny et al. 2017). SOC stocks and sequestration rates expressed in CO_2 equivalent can be a straight forward metric.

Two primary attributes of agroforestry have been identified in this area (Wise and Cacho 2005). The first is direct near-term C storage through accumulation of stocks in the form of live tree biomass, wood products, SOC and protection of existing products. The second benefit involves potential to offset GHG emissions through energy substitution, material substitution and reduction of fertilizer inputs (Wise and Cacho 2005). When synthetic fertilizers are used, they cause significant increases in GHG emissions from both direct emissions of N_2O and CO_2 emissions from their production, transport and application. Low input agriculture, such as those practiced in southern Africa, results in low yield, and this requires more land (clearing of more forest land) to off-set the yield gap.

When emissions from fertilizer and potential land use change are taken into account the carbon footprint of maize production under business as usual is estimated at 1–5 Mg CO_2eq per ha of maize grain (FAO 2015). For example, in Zambia maize production at three different intensities of nitrogen fertilizer use (0, 25, 85 kg Nha^{-1}), average annual emissions were estimated at 0.1–0.6 Mg CO_2 eq ha^{-1} (FAO 2015). On the other hand, leaf biomass from agroforestry when applied at 5 Mg ha^{-1} can provide N input of 60–150 kg ha^{-1}, and this can support maize yields of up to 4 Mg ha^{-1} without any added synthetic fertilizer (Sileshi et al. 2014a, b). Kim (2012) demonstrated that in *Gliricidia*-maize intercropping in Malawi, it is possible to reduce synthetic fertilizer use by 48 kg N ha^{-1} year^{-1} while still maintaining yields of up to 4 Mg ha^{-1}. Consequently, 0.48 kg ha^{-1} year^{-1} N_2O emissions could be avoided (Kim 2012). With the potential for N_2O mitigation of

0.12–1.97 kg ha^{-1} year^{-1} the *Gliricidia*–maize intercropping at Makoka in Malawi was also estimated to mitigate 3.5–4.1 Mg CO_2 eq ha^{-1} year^{-1} (Kim 2012).

Agroforestry systems can also contribute to GHG emissions, especially in terms of soil nitrous oxide (N_2O) and methane (CH_4) emissions. However, scarcity of comparative studies (agroforestry vs. conventional or forests) in Africa and Asia limits our ability to make concrete statements. According to a recent global synthesis (Kim et al. 2016) soils under agroforestry emitted 7.7 kg N_2O ha^{-1} year^{-1}. Considering differences in net emissions between agroforestry and adjacent agricultural land, the analysis showed no clear direction in net CH_4 and N_2O emissions. Differences in emissions between agroforestry and agriculture were: -0.1 kg CH_4 ha^{-1} year^{-1} and -2.7 kg ha^{-1} year^{-1} (Kim et al. 2016). Indeed, net soil CH_4 emissions were reduced when agriculture was shifted to improved fallow, slash-and-burn systems and tree plantations on arable land, but increased with a change to shaded perennial-crop systems (Kim et al. 2016).

N_2O emission is mainly driven by availability of N. In terrestrial ecosystems, the most favourable conditions for N_2O production are when soil water filled pore space is 60–90%, which more frequently occurs in humid tropical forests, and in savannas during the rainy season (Castaldi et al. 2006). In arid and semiarid areas, conditions are generally limiting for significant N_2O production. In cropland areas, high N_2O emissions are favoured by the addition of extra N inputs from either organic or mineral N sources (Valentini et al. 2014). In sequential agroforestry systems (e.g. improved fallows and rotational woodlots), N originating from mineralization of the organic matter after conversion and mineralization of soil organic matter stimulated by tillage is expected to lead to N_2O emissions. However, only at suitable soil water content can high N_2O fluxes be expected. Based on studies from forest ecosystems (Valentini et al. 2014), we assume that N_2O emissions will be higher during the first year after cutting tree, and emissions decrease exponentially with time. Kim (2012) estimated the N_2O mitigation potential of *Gliricidia*–maize intercropping in Malawi at 0.48 kg N_2O ha^{-1} year^{-1} or 0.14 Mg ha^{-1} year^{-1} CO_2 eq. The N_2O emission observed in *Gliricidia*–maize intercropping in Malawi is comparable to annual N_2O emission recorded by Rees et al. (2006) from burned miombo woodlands (0.50 kg N_2O ha^{-1} year^{-1}) and grassland (0.42 kg N_2O ha^{-1} year^{-1}) but higher than in protected woodland (0.25 kg N_2O ha^{-1} year^{-1}).

The production of CH_4 typically occurs in wetlands and saturated soils, anaerobic hotspots in unsaturated soils, mostly associated with organic inputs and intense mineralization (Valentini et al. 2014). CH_4 is also produced by enteric fermentation in ruminants, and invertebrates especially termites. Soils have been shown to be both CH_4 sources and sinks. Forest soils are the most active sink for CH_4, followed by grass lands and cultivated soils (Kim et al. 2016). The CH_4 uptake potential of cropland soils is reduced by cultivation and the application of ammonium fertilizers (Dutaur and Verchot 2007). As in seasonally dry forests and savannas (Valentini et al. 2014), soils under agroforestry are expected to be net CH_4 sinks. According to a recent global synthesis (Kim et al. 2016) soils under agroforestry oxidized 1.6 kg CH_4 ha^{-1} year^{-1}. The largest reduction in net CH_4 emissions (or CH_4 uptake of -3.2 kg ha^{-1} year^{-1}) was recorded under improved fallows. The greater CH_4 uptake is probably related to greater soil pore space and reduced soil bulk density (Sileshi et al. 2014a, b) under agroforestry compared with agricultural fields (Kim et al. 2016). Compared to the conventional maize cropping systems, *Gliricidia*-maize intercropping uses less or no synthetic N fertilizer and may have the potential to mitigate CH_4 emissions.

18.3 Evidence for Productivity, Adaptation and Mitigation Benefits

About 1.2 million people around the world depend upon agroforestry farming systems (World Bank 2004) and out of about 2220 million ha agricultural land (Bartholomé and Belward 2005) more than 40% of it had 10% tree cover and 13% had > 30% tree cover sequestering 47.37 Pg biomass C (Zomer et al. 2016). In the year 2010, the average value of C sequestration by agroforestry tree was 24 Mg C ha^{-1}. The total land under agroforestry and amount of biomass C sequestered globally and in regions of Asia and Africa is depicted in Tables 18.2 and 18.3.

Agroforestry covers a complex set of practices, and there are multiple ways of classifying these practices (Nath et al. 2021). The productivity, adaptation and mitigation benefits of the different agroforestry practices are expected to be context-specific as the tree species used and management practice are different. Unfortunately, in some reviews and meta-analyses there has been a tendency to bulk agroforestry practices and presenting aggregate results. This can obscure real effects of interventions. To avoid this, we encourage future authors to analyse data and present information according to the context in which a specific agroforestry technology is practiced. Most agroforestry practices in Africa and Asia fall under three broad categories, namely, agrisilvicultural, agrosilvopastoral and silvopastoral systems (Nath et al. 2021; Shin et al. 2020), which can further be broken down in to

Table 18.2 Total agricultural land under agroforestry (tree cover > 10%, > 20% and > 30%) in different regions of Africa and Asia

Region	Total agricultural land (million ha) with tree cover of			Total agricultural land
	> 10%	> 20%	> 30%	
North Africa/Western Asia	12	6	4	114
Sub-Saharan Africa	109	53	35	397
Northern & Central Asia	87	24	9	247
South Asia	34	12	7	183
Southeast Asia	127	98	77	165
East Asia	80	37	17	180
Global Total	895	476	298	2218

Actual figures may slightly differ because of conversion from km^2 to million ha and rounding up the figures

Source: Modified from Zomer et al. (2014)

Table 18.3 Total biomass C (Pg C) on agricultural land and average per hectare biomass carbon (Mg C ha^{-1}) in the year 2010 globally and by regions of Africa and Asia and contribution by trees

Region	Total biomass Carbon (Pg C)	Average biomass C (Mg C ha^{-1})
Eastern and Southern Africa	2.30	14.6
North Africa	0.11	7.3
West and Central Africa	5.45	22.8
Central Asia	0.47	5.7
East Asia	2.53	14.1
South Asia	2.48	13.6
Southeast Asia	10.69	64.8
Western Asia	0.79	8.2
Global		
Agricultural baseline	11.08	5.0
Contribution by trees (agroforestry)	36.29	24.0
Total	**47.37**	**29.0**

Source: Zomer et al. (2016). 1 fg = 10^{15} g = 1 billion tonnes

specific practices with local relevance. Agrisilvicultural systems are defined as a combination of trees and crops on a unit area of land, and the main practices are improved (rotational) fallows, intercropping, alley cropping, parklands, plantation crop combinations, woodlots, shelterbelts and windbreak on crop land (Shin et al. 2020). Agrosilvopastoral systems are defined as a combination of trees with crops and livestock, with the main practices in Africa and Asia being home gardens (Shin et al. 2020).Silvopastoral systems are defined as integration of trees and livestock on grazing/range lands, and the main practices are trees on rangeland or pastures, fodder banks, and plantation crops with pasture and animals (Nath et al. 2021; Shin et al. 2020).In the following sections we will briefly describe the various agroforestry practices and provide evidence for the different benefits using specific examples from Africa and Asia.

18.3.1 Improved Fallows, Relay Cropping, Intercropping and Alley Cropping

Improved fallows consist of deliberately planted species usually legumes with the primary purpose of fixing nitrogen as part of a crop-fallow rotation (Akinnifesi et al. 2010). The legumes can be planted as either single species or mixed stands. Compared to single-species fallows, mixed-species fallows are believed to increase the biodiversity and sustainability of the fallow system, provide insurance against failure, produce multiple products, improve utilization of available plant growth resources and reduce build-up of pests (Sileshi and Mafongoya 2003). Improved fallows using *Sesbania sesban* (hereafter *Sesbania*), *Tephrosia* spp. (*T. vogelii* and

T. candida) and *Leucaena* spp. have been widely tested on farmers' fields in Zambia and this technology has now spread to other parts of southern Africa (Akinnifesi et al. 2010).

Relay cropping involves planting fast-growing nitrogen-fixing legumes *Sesbania, Tephrosia* and pigeon pea (*Cajanus cajan*) when annual crops such as maize have already been well established, usually within 2–4 weeks of crop sowing (Akinnifesi et al. 2010). The legumes continue to grow after the crop harvest throughout the off-season. As farmers prepare land for the next season, they clear-cut the legume and incorporate the biomass into the soil. The yield levels are usually less than those achieved using intercropping and improved fallow systems, but the benefit of trees can be seen immediately after one season of tree growth.

Another extension of improved fallows is permanent tree-cereal intercropping. Trees in this system are typically coppicing leguminous species; i.e., species whose leaves and twigs can be cut 2–3 times a year and yet re-sprout copiously. The best-known form of this is the intercropping of *Gliricidia sepium* (hereafter *Gliricidia*) with maize in Malawi and Zambia (Akinnifesi et al. 2010).

When arable crops (sometimes fodder legumes and grasses) are cultivated in alleys formed by hedgerows of trees or shrubs (usually planted in close space in paired rows and distance of hedgerows varying from 4 to 6 m), the system is called alley cropping or hedgerow intercropping system. The system is more effective and useful for sloping lands in high rainfall areas where the problem of soil erosion is acute. The hedgerows (usually planted across the slope) are cut at 1 m height at crop sowing/planting time and kept pruned during the cropping season to prevent shading and to reduce nutrition and moisture competition with food crops. The hedgerows are allowed to grow when there are no crops. The pruned biomass is used as mulch or as source of green manuring or sometimes also as fodder. Leguminous species such as *Gliricidia sepium, Leucaena leucocephala, Pithecellobium dulce, Morus alba, Cassia seamea, Sesbania sesban* and perennial *Cajanus cajan* are commonly grown as hedgerow plants. In China, major change in alley cropping has been in widening of the tree rows and a reduction in tree density to make the system compatible with machine-based operations. For example, in alley cropping of *Paulownia tomentosa* in the Henan and Shandong provinces, the distance between rows is found to be 18–80 m and similar is true with *Populus deltoides, Gingko biloba* and *Ziziphus jujuba* trees (Huang et al. 1997).

18.3.1.1 Productivity Benefits

One of the direct benefits of these practices is the increase in yields of staple crops such as maize. A meta-analysis of productivity under these practices across sub-Saharan Africa (Sileshi et al. 2008) has demonstrated significant increases in maize yield. Our analysis of data relevant to southern Africa indicate that on average, *Gliricidia*-maize intercropping gives 55–350% yield increase over the control across experimental sites in Malawi, Tanzania, Zambia and Zimbabwe. In improved fallows and relay intercropping, *Sesbania* gave 160–583% increase, while *Tephrosia* gave 17–233% increase over the control.

According to State of Forest Report (SFR 2013) in India, volume of trees under agroforestry is 1124 million m^3 providing a range of benefits which at times may outweigh the negative impacts on crop yield. A reduction in crop yield might be acceptable to smallholder farmers, if fruits are sold at reasonable price or wood is produced on-farm so that they need not to purchase. Soni et al. (2017) compiled information on improvement in system productivity and resource utilization by different agroforestry systems. When maize was cultivated as inter-crop with red alder (*Alnus rubra*), 32–58% of the total nitrogen in alley-cropped maize came from nitrogen fixed by trees (Jose et al. 2004). The tree components of hybrid poplar and silver maple (*Acer saccharinum*) contributed through leaf litter and stem flow 10.99 and 15.22 kg N ha^{-1} $year^{-1}$, respectively (Smith 2010). Peanut mainly uses N in the surface soil (10–15 cm), but when cultivated with *Choerospondias axillaris*, the tree used N from dipper soil (>40 cm) increasing system N use efficiency compared with the peanut monocropping (Zhang et al. 2008). Similarly, when vegetable bottle gourd (*Lagenaria siceraria*) cultivated with *Acacia auriculiformis* and sweet orange (*Citrus sinensis*) or *A. auriculiformis* and guava (*Psidium guajava*) gave maximum profit as compared to monocropping (Banerjee and Dhara 2011).When crops cultivated in rotation of barley (*Hordium vulgare*)-cluster bean (*Cyamopsis tetragonoloba*) or barley-pearl millet or mustard (*Brassica juncea* var. CS 55 and CS 56)-cluster bean as intercrops with fruit trees goose berry *(Emblica officinalis*), Bael (*Aegle marmelos*) and karonda (*Carissa carandas*)in semi-arid hyperthermic camborthids soils irrigated with saline water were more profitable as compared to sole crops (Dagar et al. 2016b).Thus, there are numerous examples across different agroclimatic regions which prove that inter-cropping with trees and fruit trees is more profitable, sustainable and viable and meets the diverse needs of the farmers.

In China, intercropping with *Paulownia elongata, Ziziphus jujuba* (Chinese date) and *Vernicia fordii* (tong tree) has been found very promising. When grown with intercrops, tong tree produced 261 kg oil per ha, an increase of 200% compared to sole plantations besides intercrop yield, which in individual crop was peanut (810 kg ha^{-1}), rape seed (428 kg ha^{-1}), day lily *Hemerocallis fulva* (322.5 kg ha^{-1}), sweet potato (10.13 Mg ha^{-1}), potato (10.0 Mg ha^{-1}) and water melon 21.6 Mg ha^{-1} (Zhaohua et al. 1991). These crops improved soil conditions to great extent, increasing porosity from 50.8% to 64.3% and reduced specific gravity from 1.34 g m^{-3} to 0.98 g m^{-3} after 5 years of intercropping. The organic carbon and total N and P increase from 1.23%, 0.041% and 0.08% to 2.10%, 0.066% and 0.012%, respectively during the same period. Intercropping with Paulownia (planted in 5 m $\times$ 10 m to 5 m $\times$ 40 m space) had advantage that the tree has deep root system (75% roots in 40–80 cm) and can take moisture from deeper layers without having competition with intercrops. Paulownia reduced wind speed between 21% and 51%, evaporation rate 9.7% during day (4.3% during night), moisture in upper soil layers increased 19.4% and air temperature was down between 0.2 and 1.2 °C in summer. The increase in yield of intercrops was 6–23% in wheat, about 20% in millet and 7–17% in maize (Zhaohua et al. 1991). Similarly having intercrops with *Z. jujuba* economic benefit of 100% was gained and after 10 years the tree started bearing fruits with an average of 6 Mg ha^{-1} per year. Zhaohua et al. (1991) evaluated different spacing of *Paulownia elongata* and observed a biomass of 55.1, 27.5, 18.4, 13.8 and 11.0 Mg ha^{-1} at 5 m × 10 m, 5 m × 20 m, 5 m × 30 m, 5 m × 40 m, and 5 m × 50 m spacings, respectively. Intercrops 5 m × 10 m spacing was optimum for highest economic gains. A plantation of 8 years contributed dry leaves equivalent to 465.2, 232.6 and 116.3 kg N ha^{-1} at 5 m × 10 m, 5 m × 20 m and 5 m × 40 m spacings, respectively. Eight years old plantation in 5 m × 20 m space produced 2.94 Mg ha^{-1} dry leaves, which were applied in 1 ha area cultivated with wheat and cotton which produced 30.6% and 19.8% more yield as compared to when no leaves were incorporated.

18.3.1.2 Adaptation Benefits

The improved fallows have been found to increase rain use efficiency (RUE) in Zambia and Nigeria (Sileshi et al. 2011). Further results from Malawi and Zambia show significant improvement in RUE under agroforestry during extremely dry and wet seasons (Sileshi et al. 2011). In Malawi, *Gliricidia*-maize intercropping amended with 50% of the recommended fertilizer had consistently higher RUE even in extreme rainfall years. Maize-Gliricidia intercrops also had the lowest inter-annual variability (CV 30.2%). On two sites in Zambia, monoculture maize grown with the recommended dose of fertilizer was the most efficient in rainfall use closely followed by Gliricidia-maize intercropping. The lowest RUE with higher inter-annual variability was recorded in unfertilized maize on all sites. Similarly, in a study conducted in KwaZulu-Natal, pigeon pea intercropped with maize had a higher water use efficiency as compared to sole treatments (Hluyako et al. 2017). Analysis of long-term data from Zambia (Sileshi et al. 2012) also shows that these practices can off-set the effect of extremely wet or dry conditions and reduce yield variability. This has significant implications for climate change adaptation. In addition, the trees provide soil cover and contribute to better microclimate (shade, windbreak, etc.).

Land under agroforestry has been shown to be less susceptible to runoff and erosion than continuous cropping due to the soil cover provided by trees. For example, Phiri et al. (2003) found enhanced water infiltration, water holding capacity and reduced runoff under *Sesbania* improved fallows compared to fields continuously cropped with maize in Zambia. Similarly, soil loss was 30–100% lower under agroforestry trees grown in rotational fallows than under continuous maize in Zimbabwe (Nyamadzawo et al. 2012). This is expected to improve the water and nutrients use efficiency, reduce production risks and increase incomes.

In Malawi and Mozambique, intercropping pigeon pea with maize has been demonstrated to reduce the risk of crop failure and improve profitability (Rusinamhodzi et al. 2012; Snapp et al. 2010). According to Kamanga et al. (2010) maize cropped with pigeon pea or *Tephrosia* in this fashion was less risky for resource-poor farmers compared to fully fertilized maize, which had acceptable

Fig. 18.1 This Malawian farmer practiced *Tephrosia*—maize relay intercropping (left) to restore fertility of her land. After cutting part of the *Tephrosia* stand, she harvested enough firewood. The stack of firewood (right) represents only a small portion of the stand she cut. (Photo: GW Sileshi)

risk only for resource-endowed farmers in central Malawi. Similarly, Sirrine et al. (2010) found that the most vulnerable households in southern Malawi are better of relay cropping pigeon pea or *Tephrosia* with maize than growing maize with the recommended fertilizer. Using historical rainfall records and simulated yield in northern Malawi, Snapp et al. (2013) also showed that pigeon pea-maize intercropping can meet the household food needs (calories and proteins) in 73–100% of the years across variable rainfall patterns, while fully fertilized maize can achieve this in only half the households. Pigeon pea production has also been successfully integrated with energy-saving stoves, and this has reduced the frequency of buying and collecting fuel-wood in parts of Malawi (Orr et al. 2015).

Agroforestry practices can partly address this problem because planting trees on farmland moves the source of firewood closer to home (Fig. 18.1). Thus, the time and labour spent by women in search of fuelwood can be reallocated to food production and childcare (Orr et al. 2015). For example, in Malawi, 92–101% of the domestic fuelwood needs were met from a hectare of 2–3 years old *Sesbania* trees (Kamanga et al. 1999). This can also help reduce the pressure on natural forests. In Tanzania, plant combinations with higher proportions of pigeon pea conferred greater resilience, especially in seasons with less precipitation (Kimaro et al. 2019).

In India, the major timber supply to industry and domestic needs comes from farm grown trees like poplars (*Populus deltoides*) and *Eucalyptus*. Poplar cultivation is presently spread over 0.312 million ha, 99% of which is grown in agroforestry by over 0.3 million small growers, 60% being inside fields and 40% on field boundaries. Twenty to thirty million poplar saplings are planted annually by around 60,000 small growers. Each year, poplar produces 8 million tone fresh timber, 1.8 million tonnes pulpwood, 3 million tone firewood, and generate over 100 million person-days employment largely in rural areas where job opportunities are very less (Newaj et al. 2016). Similarly, the clonal eucalyptus plantations benefited thousands of farmers who planted 8 million ha during 1992–2007 (Lal 2015b) and the area is increasing every year showing the popularity of the clonal Eucalyptus plantation. Dagar et al. (2016a) found that clonal *Eucalyptus tereticornis* was the most suitable and economically viable with rice-wheat cropping system in waterlogged areas when planted on ridges (66 m apart) in paired rows (1 m × 1 m space). After 3 years of growth the water table could be lowered to 85 cm from surface and after 5 years to 2 m depth. In this system, a dry biomass of 49.5 Mg ha^{-1} (including 13.4 Mg ha^{-1} root biomass) (timber volume 65.4 m^3 ha^{-1}) was obtained and about 25 Mg ha^{-1} C was sequestered after 6 years of growth. In block plantation (2 m × 2 m space), it could produce 193 Mg ha^{-1} biomass (timber volume 204 m^3 ha^{-1}). From a normal plantation (assuming 150 Mg ha^{-1}) a farmer may get minimum of INR 300,000 per ha (that time ~ US$50,000 per ha) in 4 years of rotation. teak (*Tectona tereticornis*)-based agroforestry model (after 20 years) could provide reasonably good income in rain-fed dry region having papaya and field crops as intercrop. Teak plantation on bunds or in alleys has been adopted by farmers at large. Sapota (*Manilkara achras zapota*) fruit with teak and grasses has also been widely adopted on hilly land in dry regions (Newaj et al. 2016).

In north-eastern Himalaya regions *Alnus nepalensis*-based agroforestry system is most popular. Large cardamom (*Amomum subulatum*) and turmeric (*Curcuma domestica*) are most common remunerative shade crops cultivated with *Alnus*. The cardamom agroforestry stored 3.5 times more carbon than the rain-fed agriculture showing potential mitigation possibilities of the agroforestry and cost benefit analysis showed that the cardamom agroforestry is profiting the farmers by 5.7 times more compared to the rain-fed agriculture. The annual production of woody biomass in cardamom-based agroforestry ranged between 4.5 and 5.5 Mg ha^{-1}.

18.3.1.3 Mitigation Benefits

Introduction of trees in cropping systems has the potential to increase biomass C as tree biomass consists of 46–51% C (Kim et al. 2016). This can also enhance soil C sequestration through enhanced fine root production, rhizo-deposition, and litter fall (Kaonga and Bayliss-Smith 2009; Beedy et al. 2010; Lorenz and Lal 2014). The estimates of carbon accumulation in different agroforestry systems ranged from 0.29 to 15.2 Mg ha^{-1} year^{-1} in aboveground plant component and from 30 to 300 Mg C ha^{-1} year^{-1} for soil up to 1 m depth (Nair et al. 2009a, b). According to a recent global synthesis (Kim et al. 2016), average C increments in various agroforestry systems were 0.3–7.7 Mg ha^{-1} year^{-1} in tree biomass and 1.0–7.4 Mg ha^{-1} year^{-1} in soils. However, this differed between simultaneous (where trees and agricultural crops are grown together) and sequential (where trees and crops are grown alternately on the same piece of land) plantations. On average, C sequestration in aboveground biomass was estimated at 5 Mg C ha^{-1} year^{-1} in simultaneous systems and 6.2 Mg C ha^{-1} year^{-1} in sequential systems in tree stands aged 5–25 years (Kim et al. 2016).

In the case of improved-fallows we did not estimate CO_2eq under *Tephrosia vogelii, Sesbania sesban and Cajanus cajan* for 20-year rotations because these species typically grow only for 2–3 years. Biomass C is only accumulated during the fallow phases of 2–3 years, after which trees and shrubs are harvested and incorporated into the soil or used as fuelwood. Net C accumulation rates, and thus the amount of C that is credibly and permanently sequestered from the atmosphere is thus substantially lower than biomass C build-up suggests (Luedeling et al. 2011).

Using input data from the Malawi Agroforestry Food Security Program, we estimated the GHG emission/removal potentials of *Gliricidia*-maize intercropping and *Tephrosia* relay intercropping over a 20-year period relative to the baseline. The baseline was conventional maize cultivation, where crop residues are removed and burnt, and fields are left bare from May to November. The net removal using *Gliricidia*-maize intercropping was −33 Mg CO_2 eq ha^{-1} (likely range: −27 to −47 Mg CO_2 eq ha^{-1}) over 20-year period. Using *Tephrosia* relay intercropping the net removal was estimated at was −70 Mg CO_2 eq ha^{-1} (likely range: −48 to −91 Mg CO_2 eq ha^{-1}) over 20-year period. However, the net removal using *Gliricidi*a-maize intercropping widely varied with sites, while such variations were smaller under Tephrosia relay intercropping (Table 18.2).

Data on soil C storage in agroforestry systems is scanty in much of Africa and Asia. However, the few studies reveal significant improvements over conventional practices such as maize monoculture. In Malawi, Makumba et al. (2006) found that soil C in a *Gliricidia*–maize intercropping is roughly doubled after 7–10 years compared to sole maize. A more recent reanalysis of the data showed an annual net gain of 3.5 Mg C ha^{-1} $year^{-1}$ in the soil under *Gliricidia*–maize intercropping (Kim 2012). In Indonesia, an increase of SOC content by 4 g kg^{-1} (0.4%) was reported when degraded land cover was transformed to multistrata agroforestry (Gusli et al. 2020).

Nair et al. (2009b) reported soil C stock in improved fallows, tree intercropping and alley cropping under tropical agroforestry systems ranged 123–149 Mg ha^{-1}, 27–78 Mg ha^{-1} and 10–25 Mg ha^{-1}, respectively. In West Africa Sahel, Bado et al. (2020) concluded that including *Ziziphus mauritiana* trees at the density of 80 plants ha^{-1} to the low input cropping systems (millet, cowpea) of smallholder farmers improved agricultural productivity and farmers' incomes and ensured sustainable management of soils, land resources, and ecosystem services.

Ståhl et al. (2002) observed in fallows of eastern Kenya *Sesbania sesban* had C stock of 5.55 Mg ha^{-1} in below ground and 21.3 Mg ha^{-1} in above ground biomass. The Kenya Agricultural Carbon Project has promoted agroforestry helping almost 30,000 farmers in western Kenya to grow over three million indigenous agroforestry trees, alongside learning other sustainable land management practices; such as composting, mulching, and application of livestock manure. Under this project about 345,000 tons CO_2 between 2010 and 2016 has been sequestered, while improving agrobiodiversity, food security and adaptation to climate change as co-benefits. The project was a game changer, where farmers who had experienced a decline in crop and livestock yields over time and severe environmental degradation, achieved over 150% increase in yields over a period of 8 years (Agroforestry Network 2019). Increasing yields was the main economic incentive for the farmers to engage in the project, and since the start of the project savings among farmer families have increased—along with a greater resilience to a wide range of shocks, including climate change impacts. When the project ends in 2030, the expected sequestrated amount of carbon will be about two million tons (Agroforestry Network 2019).

In India, C sequestration potential of AF systems has been estimated as 0.25–76.55 Mg ha^{-1} year^{-1} for tree and 3.98 Mg ha^{-1} year^{-1} for soil organic carbon (Dhyani et al. 2016). However, this potential varies with region, types of species, age of AF system, spacing of trees, environmental condition and soil types. In rain-fed dry climate, *Dalbergia sissoo* at age 11 years was able to accumulate 48–52 Mg ha^{-1} of biomass and carbon dynamics involving different pruning treatments were studied in an agrisilvicultural system where tree biomass was 23.61–34.49 Mg C ha^{-1} with black gram-mustard (Newaj et al. 2008). Rai et al. (2002) reported 1.36 Mg C ha^{-1} year^{-1} sequestered by *Anogeissus latifolia* intercropping in dry region of Bundelkhand while Swamy et al. (2003) and Swamy and Puri (2005) reported 1.28 Mg C ha^{-1} year^{-1} in belowground and 6.3 Mg C ha^{-1} year^{-1} in aboveground in *Gmelina arborea*-based system. Yadava (2011) and Rizvi et al. (2011) reported 0.34–0.88 Mg C ha^{-1} year^{-1} in boundary plantation of *Eucalyptus*; 3.86–4.56 Mg CC ha^{-1} year^{-1} in *Populus deltoides*; and 1.4–2.73 C ha^{-1} year^{-1} in *Dalbergia sissoo*.

Tropical bamboo (*Bambusa bambos*) produced total aboveground biomass 287 Mg ha^{-1} with a mean annual production of around 47.8 Mg ha^{-1} year^{-1}, almost twice that of the Eucalyptus clones. The total biomass of mature bamboo at 6 years is higher than that of teak at 40 years, that is, 149 Mg C ha^{-1} as compared to only 126 Mg C ha^{-1} for teak. Every 5 years it would produce at least 86 Mg ha^{-1} biomass and sequester 43 Mg C ha^{-1}, almost twice as much as a teak plantation under the similar conditions (Newaj et al. 2016). Thus, to achieve higher level of carbon sequestration, sustainable bamboo management, regular harvesting and utilization for durable products can be advocated. Jat et al. (2016) advocated that afforestation of degraded lands has large potential of biomass production and SOC sequestration (7.20–9.82 Tg C per year (Tg = 10^6 Mg). SOC sequestration rate and total SOC sequestration potential varied in restoration of different degradation processes [SOC sequestration rate: water erosion 80–120 kg ha^{-1} year^{-1}, wind erosion 40–60 kg ha^{-1} year^{-1}, salinization 120–150 kg ha^{-1} year^{-1}, waterlogging 40–60 kg ha^{-1} year^{-1}; and SOC sequestration potential: 2.62–3.94, 0.43–0.65, 0.49–0.62 and 0.12–0.19 Tg C year^{-1}, respectively]. They also reported the carbon-storage potential of agroforestry systems to range from 1.8 to 35.13 Mg ha^{-1} in different climatic regions of India.

In China, a comprehensive meta-analysis of soil C sequestration rates in agroforestry systems (AFS) derived from 43 studies was undertaken by Hübner et al. (2021) top soils (0–20 cm, 97 sites) and at two sub-soil layers (20–40 cm, 73 sites; 40–60 cm, 54 sites). The results showed highest C sequestration rates for the AFS-type shelterbelt in top soils (0.92 Mg ha^{-1} year^{-1}), upper sub-soils (0.72 Mg ha^{-1} year^{-1}) and lower sub-soils (0.52 Mg ha^{-1} year^{-1}), followed by agrosilvicultural systems (0.70, 0.48 and 0.43 Mg ha^{-1} year^{-1}, respectively) and silvopastoral systems (0.23, 0.08 and 0.02 Mg ha^{-1} year^{-1}, respectively). They concluded that besides the AFS-type and the initial SOC, soil type plays a decisive role for the efficiency of soil C sequestration by agroforestry. Our meta-analysis provided evidence that existing AFS in China, particularly shelterbelts and agrosilvicultural systems, are effective practices to increase SOC stocks, both in top- and sub-soils and especially in the subtropical climate zone. Niu et al. (2021) observed that compared with the 1980s, mean SOC stock in the 0–100 cm soil layer significantly increased (by 0.69 kg m^{-2}) over the 40-year period in the plain with change in land use and management practices in the region by converting of crop land into orchards. SOC stock in the 0–100 and 100–1000 cm soil layers accounted for 16.9% and 83.1%, respectively, of the total SOC stock in the 0–1000 cm soil profile.

18.3.2 Agroforestry Parklands

Scattered trees in crop land, often known as 'agroforestry parklands' are widespread traditional practices in the semi-arid tropics (Boffa 1999). The best-known ones are found in the West African Sahel where *Faidherbia albida* (hereafter *Faidherbia*), *Parkia biglobosa*, *Vitellaria paradoxa* and many other species are managed together with crops such as sorghum, millet, cotton and groundnuts. In the semi-arid parts of eastern and southern Africa, *Faidherbia*, mango, *Adansonia digitata*, *Parinari curatellifolia* and *Acacia* spp. are similarly managed with crops such as maize (Akinnifesi et al. 2010). Trees in parkland systems are rarely planted but are derived from natural regeneration and are protected by farmers. Among the best known are *Faidherbia*-coffee system in Tanzania, and the *Faidherbia*-maize system in Malawi, Zambia, and Zimbabwe (Akinnifesi et al. 2010).

The poplar-wheat/barley agroforestry in northern India is akin to parkland agroforestry Poplars are among the fast-growing tree species and can be harvested at a short rotation of 6–7 years (Gera et al. 2006). Because of economic benefits associated with poplar-based agroforestry systems and their role in preventing land degradation, this land-use has been proposed as a viable option for advancing sustainable food production system in India (Pandey 2007).

Another common practice similar to parkland agroforestry is the Khejri (*Prosopis cineraria*)-based agroforestry in arid and semi-arid north-western Indian sub-continent(Fig. 18.2).The main crops in association with *P. cineraria* include pearl millet, mustard, barley, gram (*Cicer arietinum*), moth-bean (*Vigna aconitifolia*), green gram (*Vigna radiata*), black gram (*Vigna mungo*) and cluster bean (*Cyamopsis tetragonoloba*).Other important trees of this system include *Tecomella undulata*, *Acacia nilotica, A. leucophloea, A. catechu, A. senegal, Azadirachta indica, Salvadora oleoides, Calligonum polygonoides* (bush), and fruit trees *Ziziphus nummularia* and *Z. mauritiana* (Tewari et al. 2014). Recently, drip irrigation has been introduced and cotton is cultivated at large scale in parkland systems (Grewal et al. 2021; Fig. 18.3).

Fig. 18.2 Khejri (*Prosopis cineraria*) in dry areas of India (left) (Photo: AK Yadav); and cultivated pearl millet with Prosopis *cineraria*) (right). (Photo Courtesy Dr. Vikram Singh)

Fig. 18.3 Large-scale cotton cultivation on sandy soils with drip irrigation under scattered trees of *Prosopis cineraria* in north-western India. (Source: Grewal et al. 2021)

18.3.2.1 Productivity Benefits

Recent analyses suggest that agroforestry parklands are crucial to improving food security of farmers (Sileshi 2016; Leroux et al. 2022). Using meta-analysis of published studies, Sileshi (2016) showed that *Faidherbia* parklands can increase yields of maize by 150% and sorghum by 73%. Using household surveys, geospatial data and novel analyses, Leroux et al. (2022) provided evidence that parkland diversity (i.e. tree species richness and tree density) is key drivers of food availability, explaining more than half of crop yield variability in two contrasting parklands of Central Senegal. The configuration (i.e. tree density) and composition (i.e. tree species richness) of the parklands in the Groundnut Basin of Senegal are important drivers of the yield of the millet crop. The productivity benefit of agroforestry parklands is often context specific, and this depends on tree size as well as management. Mature trees have a stronger positive effect on crop productivity than young trees of *Faidherbia* (Sileshi 2016). Tree pruning has a positive effect on crop yield when it reduces the competition for light (Dilla et al. 2020).

In arid regions of western India, the interesting feature was that the yield of pearl millet, main cereal crop of the region, below the canopy of woody components in any system was not affected, rather under *P. cineraria* it increased; however, the yield of legume crops declined 5.0–19.5% (Tewari et al. 2014). The foliage of trees constitutes nutritious components of animal feed in these regions and of leguminous trees it is comparable with grass production from the pastures. In addition to crop yield *P. cineraria* provides fruit of 350–1040 g tree^{-1} used as vegetable and 19.96 Mg ha^{-1} including leaf fodder of 0.85 Mg ha^{-1} per year at 12-year age with 208 tree ha^{-1} (Singh 2009).When green gram was intercropped with fruit tree *Z. mauritiana*, the profitability was 67% and the net B: C ratio of some traditional *P. cineraria* and *A. nilotica*-based systems was > than 2 (Tewari et al. 2014). When micro-irrigation was introduced the profitability of parkland systems increased many fold (Grewal et al. 2021). Thus, the integration of trees and shrubs with annual crops provides shade, a steady supply of food and income throughout the year, arrests degradation and maintains soil fertility, diversifies income sources, increases and stabilizes income, enhances use efficiency of nutrients, water and radiation, and provides regular employment in dry regions. The importance of trees in providing household income cannot be overemphasized. Tree based agroforestry technologies have been found to contribute to income levels of households either directly through the sale of by-products such as fuel wood and/or merchantable timber (Padalia et al. 2017) and indirectly through sale of increased crop yields. According to Miller et al. (2017), trees accounted for an average of 17% of the total annual gross income for tree growing households and 6% for all rural households in Ethiopia, Malawi, Nigeria, Tanzania and Uganda. It is further argued that in Burkina Faso, Mali and Senegal, close to 50% of households obtained income from agroforestry (Binam et al. 2015).

18.3.2.2 Adaptation Benefits

In these settings, the trees significantly improve the growing conditions of crops under the canopy. For example, a meta-analysis of studies on *Faidherbia albida* parklands across Africa (Sileshi 2016) indicates 46% higher soil organic carbon (SOC) under trees than in open areas. Increased SOC content, particularly in the light fraction, is known to improve aggregate stability, porosity, hydraulic conductivity and soil structures that resist erosion. Under a range of conditions across sub-Saharan Africa *Faidherbia* increased SOC by 46%, total nitrogen by 50%, available phosphorus by 21%, exchangeable potassium by 32%, and yields of maize by 150% and sorghum by 73% under the tree canopy compared to the open area (Sileshi 2016). Dierks et al. (2021) recently showed that within one cropping season, maize obtained approximately 35 kg ha^{-1} biologically fixed N from *Faidherbia* through arbuscular mycorrhizae-mediated N uptake from beyond the maize rooting zone and two-thirds to N from tree leaf litter. Tewari et al. (2014) and Soni et al. (2017) reported many-fold increase in SOC, micro-nutrients and crop yield under *P. cineraria* and the air temperature was lower up to 2 °C under the tree canopies in dry regions in India. The trees harvested the nutrients and moisture from deeper layers making these available to crops.

On farmers' fields across Malawi and Zambia, maize planted under *Faidherbia* canopies gave 76–185% higher yields compared crops outside the canopy (Table 18.1). In addition, the trees provide soil cover and contribute to better microclimate (shade, windbreak, etc.). Moderation of the soil temperature at the time of seedling establishment is also an important component of the tree effect. Tewari et al. (2014), Sileshi (2016) and Sida et al. (2018) provide examples of considerable reduction in air and soil temperatures (closer to the optimum for crops) under *Faidherbia* and *Prosopis cineraria* canopy than outside during the day. For example, midday air temperature was about 6 °C less under the *Faidherbia* trees than in the open fields in the Central Rift Valley of Ethiopian (Sida et al. 2018). According to farmers in Nenyunga Gokwe South-West of Zimbabwe, *Faidherbia* pods can be eaten during times of hunger, farmers call it the 'hunger tree'. Its pods are also a valuable livestock feed. When the temperatures are very high, livestock also seek its shade, and as such dung and urine deposited thereby contributing to soil fertility. As such the best crop stands and higher yields are consistently recorded under *Faidherbia* canopy than elsewhere in the field (Sileshi 2016). The pods of *P. cineraria* are consumed as vegetable and also fed to livestock and tree is considered tree of life in desert. Realizing the potential of P. cineraria in arid region, a new variety (Thar Shobha) has been developed by Central Institute of Arid Horticulture in India through bud grafting which tolerates high (>48 °C) and low (−4 °C) temperature and aridity conditions (Soni et al. 2017). It is extremely drought tolerant and has high potential of production under rain-fed conditions of arid and semi-arid area. A 5-years old bud-grafted plant could yield 4.25 kg green-pods (used for vegetable) and 6.25 kg leaves (fodder) in a year with improved production technology (Soni et al. 2017). These observations emphasize the fact that planting *Faidherbia* (in Africa) and *Prosopis* (in dry regions of Indian sub-continent) in crop fields can be an important adaptation strategy to increasing climate variability.

18.3.2.3 Mitigation Benefits

In Africa, higher C storage in tree biomass has often been observed in agroforestry parklands where trees are kept for a long time. For example, in Mali, *Faidherbia* accumulated 20.3 Mg C ha^{-1} (Takimoto et al. 2008). A 6-year stand of *Faidherbia* in Tanzania accumulated 1.2 Mg ha^{-1} year^{-1} in above-ground biomass (Okorio and Maghembe 1994). *Faidherbia* lives for more than 50 years and it can accumulate significant biomass C (Beedy et al. 2016) while at the same time increasing productivity of crops planted under its canopy (Sileshi 2016). Thus, managing *Faidherbia* to cropping systems avoids the typical trade-off of increasing carbon sequestration by reducing land in food production systems.

Newaj et al. (2020) reported total carbon stock in base line (22.29 Mg C ha^{-1}), net C-sequestered over simulated period of 30 years (7.05 Mg C ha^{-1}) and carbon sequestration potential (0.49 Mg C ha^{-1} $year^{-1}$) in arid Rajasthan, India. Based on the on-station and off-station trials in South Asia, climate-smart agriculture (CSA)-based modules in irrigated ecosystem had a potential to increase the system productivity and profitability by 5–15% and 20–25% in major cereal (rice, maize and wheat)-based agrifood systems while reducing the global warming potential by 15–35% (Sapkota et al. 2017, 2019, 2020, 2021). Approximately 90% of total mitigation results from improved sink (C sequestration) and approximately 10% from reduction of emissions (Ortiz-Monasterio et al. 2010). Reduction in CH_4 emissions in agriculture can largely be achieved by following management of rice cultivation (drying and wetting, bed planting and direct sowing of rice) and regulating the feed of livestock. Best N management practices able to reduce the combined (NOx and N_2O) emissions by more than 50% and NO_3-leaching by >60%. Optimizing N-fertilizer application rates and synchronizing them to crop growth and development will improve yields while reducing costs and N_2O emissions (Verhulst et al. 2011; Sapkota et al. 2014). Mean annual N_2O emission from rice-wheat system was 1.49 kg N ha^{-1} in N75 plot and 2.97–3.04 in the plots receiving ≥150 kg N ha^{-1}.

Sapkota et al. (2017) found that zero-till with residue retention resulted in the lowest global warming potential (GWP) ranging from −3301 to −823 kg CO_2-eq ha^{-1} $year^{-1}$ compared to 4113 to 7917 kg CO_2-eq ha^{-1} $year^{-1}$ in other conventional treatments. Operational inputs (tillage, planting, and irrigation) and soil C sequestration had significant effects on total GWP. The water footprint of rice-wheat production system was about 29% less in conservation agriculture-based system compared to conventional till-based systems.

On average, the yield-scaled N_2O emissions of rice and wheat were 0.25 and 0.52 kg N_2O–N mg^{-1}, respectively Sapkota et al. 2020). Their finding suggests that N rates between 120–200 kg N ha^{-1} in rice and 50–185 kg ha^{-1} in wheat provide the most economical returns and application rates beyond these ranges would be both economically and environmentally unsustainable. Sapkota et al. (2021) evaluated Nutrient Expert (NE) tool-based site-specific nutrient management in rice and wheat crops by establishing comparison trials with farmers' fertilization practices (FFP) across the Indo-Gangetic Plains (IGP) of India and found that NE-based fertilizer management can lower global warming potential (GWP) by about 2.5% in rice, and between 12% and 20% in wheat over FFP and adoption of NE-based fertilizer recommendation practice in all rice and wheat acreage in India would translate into 13.92 million tonnes (Mt) more rice and wheat production with 1.44 Mt less N fertilizer use, and a reduction in GHG of 5.34 Mt CO_2e per year over farmers' current practice. Therefore, improving nitrogen use efficiency in croplands provides the opportunity to address the triple challenge of food security, farmers' livelihood and environmental protection, globally.

Compared with business-as-usual practices, sustainable intensification strategies (reduced or zero tillage with opportunistic diversification and precision resource management) can be more productive through increases in productivity (10–17%) and profitability (24–50%) while using less irrigation water (15–71% reduction) and energy (17–47% reduction), leading to 15–30% lower global warming potential (Kumar et al. 2018). In the scenario where early wheat sowing was combined with zero till (ZT) along with no puddling during the rice phase, it resulted in a 15–17% gain in wheat yield compared with business as usual. The advantages of direct seeded rice (DSR) were more stable through time, including reductions in irrigation water (22–40%), production cost (11–17%), energy inputs (13–34%) and total GWP (14–32%). When ZT maize was used as a diversification option instead of rice, reductions in resource use jumped to 82–89% for irrigation water and 49–66% for energy inputs, with 13–40% lower GWP, similar or higher rice equivalent yield, and higher profitability (27–73%) in comparison to the rice-based scenarios (Kumar et al. 2018). *Populus deltoides* and clonal *Eucalyptus* are common boundary and alley trees in rice-wheat cropping system in IGP. In the rice-wheat system, the substitution of rice with corn, pigeon pea and soybeans significantly reduce GHG in the north-west of the South Asian IGP (Jat et al. 2020) and these crops are better suitable to agroforestry practices. Three mitigation options, i.e., efficient use of fertilizer, zero-tillage and rice-water management, could deliver more than 50% of the total technical abatement potential (Sapkota et al. 2019).

18.3.3 Plantation Agroforestry

Modern commercial plantations represent a well-managed and profitable stable land use activities in the tropics. Tree planting combined with cash crops such as tea, cocoa, rubber, coffee and oil palm, etc., are an important strategy to optimize the productivity, profitability and enhancing livelihood opportunities. Contrary to popular belief, a substantial proportion of tropical plantation crops are grown by small holders. During the early phase of establishment intercropping is quite feasible. For example, most of the cacao production in Ghana and Nigeria comes from small holdings and intercrops like maize, cassava, banana, cucumber and sweet potato are cultivated at least during the first 4 years of planting. Many small-holder rubber plantations in Southeast Asia and tropical Africa are based on integrated crops such as soybean, maize, banana, ground nut fruit trees, coconut, black pepper and tuber crops. In Malaysia, poultry raising in rubber is a common wealth. For example, tea (*Camellia sinensis*) is often grown under a canopy of trees forming a distinctive agroforestry system (Kalita et al. 2020). Similarly, large cardamom (*Amomum subulatum*) a perennial cash crop grown traditionally beneath the natural/plantation tree cover on marginal lands and slopes (Sharma et al. 2007).

18.3.3.1 Productivity Benefits

Tea is often grown under a canopy of trees forming a distinctive agroforestry system (Kalita et al. 2020). In China, under plantation (mainly *Paulownia elongata*, Chinese fir-C*unninghamia lanceolata, Toona sinensis*) and even in forests cultivation of commercial crops like tea (*Thea chinensis*), *Cinchona ledgeriana, Coffea* spp., *Cinnamomum cassia* and medicinal *Rauwolfia yunnanensis* was found quite profitable. The yield of tea increased by an average 412.5 kg ha^{-1} and yield of rubber plantations was also high (Zhaohua et al. 1991). Further, Haishui and Kejun (1991) reported the benefits of intercropping with rubber (*Hevea brasiliensis*) planted in 2 m $\times$ 12 m or 2 m $\times$ 15 m spacing in southern China. Crops intercropped with such trees included sweet potato, maize, sorghum, cassava and peanut. Medicinal crops such as *Alpinia oxyphylla, Amomum longiligulare*, and *Morinda officinalis* were of great interest. When coffee grown in partial shade of rubber plantation it produced 247.5 kg ha^{-1} beans; lemon grass yielded 100–150 kg ha^{-1} citronella oil; *Alpinia* yielded 400–500 kg ha^{-1} seeds, while *Morinda* and *Amomum* gave economic yield of 250–300 kg and 80–120 kg ha^{-1}, respectively.

In Nicobar Islands (India) poultry and domestication of pigs with coconut is very old practice. Most of the coconut production in India, the Philippines, Sri Lanka, and the Pacific Islands comes from small holdings in which coconut palm is integrated with a large number of annual and perennial crops like clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum zeylanicum*), coffee, cacao, cassava, yams (*Dioscorea alata*), fodder grasses, and legumes. Grazing under coconut and cashew nut (*Anacardium occidentale*) is also common. In India, Tanzania, Mozambique and Senegal, smallholders grow cashew nut commonly (in wider spaces) with other crops. Coffee is integrated with other crops like banana and maize in Ethiopian highlands, Colombia, and Kenya. Domestication of large cardamom (*Amomum subulatum*) plantations under Alder (*Alnus nepalensis*) in North-eastern Himalayan Region and its collection from the natural forests by indigenous Lepcha and Limbu tribes is an age-old agroforestry practice. Sharma et al. (2009) reported that the yield of finished cardamom under Alder (454 kg ha^{-1} $year^{-1}$) was almost double than produced under natural forest canopy (205 kg ha^{-1} $year^{-1}$). This system has the potential to generate net income of INR 80,000–90,000, i.e., ~US$ 2200) per ha per annum. Besides *Alnus nepalensis*, there are 29 other tree species, supporting this plantation crop. Singh et al. (2014), Dagar et al. (2014, 2020) and Dagar and Tewari (2017) have given a detailed account of production potential of various plantation crops.

Cost benefit analysis from the cardamom agroforestry in Eastern Himalayas showed it profited farmers 5.7 times more compared to the rain-fed agriculture (Sharma et al. 2007). In China, tea productivity increased between 50% and 72% when grown in conjunction with *Alnus nepalensis* and is attributed to the increases in the soil community biomass (Mortimer et al. 2015). India is the second largest tea producer in the world, while North East India with 81% of tea cultivation area represented by tea agroforestry accounts for 80% of total tea production in the country (Tea Board of India 2014).

18.3.3.2 Adaptation Benefits

Plantation-based cropping systems have been widely adapted throughout the tropics both in humid and semi-arid ecologies and Asia and Africa are no exceptions. A sizeable data has been generated (Kumar and Nair 2011; Luedeling et al. 2011; Dagar et al. 2014, 2020; Dagar and Minhas 2016; Dagar and Tewari 2017) which establishes the fact that these systems are economically profitable, environmentally sustainable and socially acceptable and not only sustain livelihood security but also mitigate climate change through sequestering huge quantity of carbon. In the Yunnan Province of China, Rigal et al. (2020) studied the impact of shade trees on the soil chemical, biological and biochemical components, especially during the dry season. This positive impact included higher soil organic matter (+10%) and more abundant soil microbial communities (+64%) under shaded coffee than under open coffee. Similarly, the conservation value for water in the cardamom agroforestry was found to be 81% which is higher compared to the rain-fed agriculture system (Sharma et al. 2007). Under proper management, plantation agroforestry can also improve microclimatic conditions that reduce abiotic stress and facilitate the performance of understory crops (Blaser et al. 2018).

18.3.3.3 Mitigation Benefits

A wide range of carbon storage potential is found in plantation-based cropping systems. Nair et al. (2009b) estimated potential sequestration rates of 5.9 Mg C ha^{-1} $year^{-1}$ for cacao agroforests of Cameroon, 6.3 Mg ha^{-1} $year^{-1}$ for shade coffee in Togo and between 0.3 and 1.1 Mg ha^{-1} $year^{-1}$ for agroforestry in the Sahel. The carbon sequestration in humid and sub-humid areas in different land uses/practices such as conservation agriculture, agroforestry, and afforestation ranged 0.3–0.8, 0.2–3.1, and 4.0–4.8 Mg C ha^{-1} $year^{-1}$, respectively. The aboveground C stock of mixed tree species (>20-cm girth) in 839 home gardens of the Western Coast ranged from 16.3 to 35.2 Mg ha^{-1} with a mean of 24.3 Mg ha^{-1} (Kumar and Takeuchi 2009; Kumar 2011). In tea agroforestry in India, Kalita et al. (2020) estimated the above-ground biomass C stocks at 32.1 Mg ha^{-1}, belowground biomass C at 8.34 Mg ha^{-1}, and SOC stocks at 112–126 Mg ha^{-1}. According to Brahma et al. (2017) rehabilitating degraded forests through *Piper betle* agroforestry increased SOC by 22.3 Mg ha^{-1}. SOC stocks in Piper betle agroforestry was estimated at 115.9 Mg ha^{-1} or increment of 0.74 Mg ha^{-1} annually (Nath et al. 2018). Converting degraded forest into rubber tree plantations and Areca agroforestry also increased ecosystem C sequestration (vegetation + SOC) by 3.92 and 4.94 Mg ha^{-1} $year^{-1}$, respectively. Similarly, converting degraded *Imperata* *cylindrica* grassland into rubber tree plantations increased ecosystem C sequestration by 4.20 Mg ha^{-1} $year^{-1}$ in North East India (Brahma et al. 2017).

Tschora and Cherubini (2020) reported that on average, trees in the studied agroforestry plots in the Plateau region in South-Western Togo (West Africa) stored 83.7 ± 7.0 Mg C ha^{-1} and found synergies between rural development and adaptation benefits and no clear relationship between biodiversity and carbon storage, and a trade-off between high carbon stocks and crop yields. The studied plots belonged to shaded agroforests consisting of perennial crop (cocoa or coffee) which was primarily grown by the farmer, and agroforestry component including trees retained from natural vegetation (Species of *Ficus, Albizia, Ceiba pentandra* and *Khaya senegalensis*) and companion crops (oil palm and banana). Among the agroforestry trees, shade trees hold larger carbon stocks (830 kg C per tree) than fruit trees (210 kg C per tree) or oil palms (101 kg C per tree). Contribution of banana stems was found negligible (0.04% of the total carbon stocks), despite their abundance on field.

18.3.4 Woodlots

Traditionally woodlots have been managed as blocks of trees planted for the sole purpose of wood. In many parts of the world, farmers (mainly with large holdings) grow trees in separate blocks along with agricultural fields/This practice is expanding fast due to shortage of fuel wood and demand of poles and pulpwood industry. For example, bamboo poles are in great demand for orange orchards and Eucalyptus and Populus for WIMCO industries in India. Woodlots of *Casuarina equisetifolia C. glauca*, bamboo*, Populus deltoides, Eucalyptus spp, Pterocarpus santalinus, Dalbergia sissoo, Melia composita* and *Leucaena leucocephala* are popular in many parts of India (Dagar and Tewari 2017). A modification of the traditional woodlots now called is called rotational woodlots has been tested in southern and eastern Africa. In this system, nitrogen-fixing trees are grown for about 5 years, then harvested and replaced by food crops, (Akinnifesi et al. 2010). The tree species belonging to the genera *Acacia*, *Vachellia* and *Leucaena* are usually planted to improve soil fertility on degraded lands while providing a range of products including fuelwood, poles and timber. For example, in Tanzania, soil initially deficient in N and P for maize culture was replenished sufficiently with *Acacia polyacantha* and *Acacia mangium* rotational to support one cropping season of maize without fertilizer supplementation (Kimaro et al. 2007).

18.3.4.1 Productivity and Adaptation Benefits

After 5 years, soil organic carbon levels in woodlots reached levels close to natural status of *miombo* woodlands in Tanzania (Kimaro et al. 2007). These results reflect the high potential of the rotational woodlots to improve maize production after wood harvest. Rotational woodlots can satisfy household and regional fuelwood demand (Kimaro et al. 2011) and may thus reduce pressure on adjacent woodland, opening potential opportunities for payments for avoided deforestation and forest degradation. They reported biomass and carbon accumulation in wood of 5 years old trees such as *Acacia auriculiformis, A. crassicarpa, A. julifera, A. leptocarpa, A. mangium, Gliricidia sepium* and *Leucaena diversifolia* and found biomass ranging from 23.2 Mg ha^{-1} to 38.3 Mg ha^{-1} and carbon contents from 11.6 Mg ha^{-1} to 25.5 Mg ha^{-1} with carbon accumulation rate varying from 2.32 Mg ha^{-1} $year^{-1}$ to 5.10 Mg ha^{-1} $year^{-1}$ in *A. crassicarpa*.

Dagar (2014) compiled work on afforestation and agroforestry on salt-affected soils in India. It was found that 6-years old plantations of *Prosopis juliflora, Acacia nilotica, Casuarina equisetifolia* and *Eucalyptus tereticornis* when established with auger-hole technique on high pH (>10) soil produced a biomass (fire wood and small timber) of 26, 21, 19 and 15 Mg ha^{-1} $year^{-1}$, respectively (Singh et al. 1993). At another site having soil profile pH 10.1–10.6, *P. juliflora, A. nilotica* and *Tamarix articulata* produced 51, 70 and 93 Mg ha^{-1} above ground biomass after 7 years (Dagar et al. 2001; Singh and Dagar 2005). From a long-term experiment conducted in Indo-Gangetic plains on high sodic soil (pH 10.6), Singh et al. (2008) reported above-ground biomass after 10 years of plantation(planted in 2 m × 4 m space) and harvested alternate tree from each row to be 56.5, 50.8, 42.1, 41.6, 32.3, 30.8, 27.8, 26.7, 21.7 and 19.2 Mg ha^{-1} from *P. juliflora, A. nilotica, C. equisetifolia, Terminalia arjuna, Pithecellobium dulce, Eucalyptus tereticornis, Prosopis alba, Pongamia pinnata, Cassia siamea* and *Azadirechta indica*, respectively. When harvested after 14 years the maximum bole-biomass (of timber value) was obtained from *Eucalyptus* (231 kg per plant) followed by *Acacia* (217 kg), *P. juliflora* (208 kg), and *Casuarina* (197 kg), whereas *P. alba, P. dulce, T. arjuna, P. pinnata*, *A. indica* and *C. siamea* provided relatively lower bole weight of 133, 100, 97, 84, 83, and 52 kg per plant, respectively (Dagar 2014).

In Indian sub-continent, *Prosopis juliflora*, though controversial tree as it invaginates in all types of soil impacting the biodiversity, was planted in large area, particularly on highly sodic soils. It ameliorates soil through leaf litter and root exudates and also increases nitrogen in soil to the extent that a soil with pH > 10 when planted with *Prosopis* as block plantation ameliorated the soil to cultivate normal arable crops. After 10 years of plantation could reduce pH from 10.6 to 9.5 and in another experiment, after 20 years it reduced pH from 10.2 to 7.5 (Dagar 2014). Other woodlots of *Acacia nilotica, Eucalyptus tereticornis, Terminalia arjuna* and *Acacia lebbeck* reduced pH 10.2–8.4, 8.5, 7.9 and 7.9, respectively after 20 years of plantation. After 10 years of plantation, the pH was reduced to 9.5 in *P. juliflora*, 9.7 in *A. nilotica* and *P. pinnata*, 9.8 in *Terminalia*, *Eucalyptus* and *Azadirechta*, 9.9 in *Prosopis alba* and *Pithecellobium*, and 10.0 in *Casuarina* and *Cassia*. The contents of SOC increased ranging from 2.4 (*Eucalyptus*) to 4.3 (*P. juliflora*) g per kg from initial 0.8 g per kg. Thus, woodlots of various species have potential to sequester carbon and ameliorate the soil. In a 25-year-old *Grevillea robusta* tree plantation in Indo-Gangetic plains, it was found that there was appreciable carbon pool in aboveground component (131 Mg C ha^{-1}, i.e., 5.24 Mg ha^{-1} year^{-1}) and 23.4 Mg C ha^{-1}(~1 Mg Cha^{-1} year^{-1}) accumulation in belowground component.

18.3.4.2 Mitigation Benefits

The mitigation potential is different from agroforestry systems that are less frequently cut such as parklands. Woodlots that are used as biomass fuels contribute to GHG mitigation through substituting fossil fuels. In Tanzania and Zambia, C accumulation rates in rotational woodlots were estimated at 2–8 Mg ha^{-1} year^{-1} (Table 18.3). Leguminous trees and shrubs planted in improved fallows also accumulate relatively high C in biomass. For example, estimated annual aboveground plant C input were 2.5–2.8 Mg ha^{-1} year^{-1} for *Cajanus*, *Sesbania sesban* and *Tephrosia* (Table 18.3). Using our own data from southern Africa, we estimated the C storage in CO_2 equivalent for a rotation cycle of 20 years at 169–587 t ha^{-1} CO_2 eq. The C storage estimated recorded in the intercrop and woodlots are much higher than values estimated for the same tree age in regrowth and coppiced miombo woodlands and fruit trees. This is probably because of the faster growth rate of agroforestry species. Using values from the literature Luedeling et al. (2011) estimated a C sequestration rate of 1.1 Mg ha^{-1} year^{-1} for a woodlot in the Democratic Republic of the Congo (DRC), at a cost of 4–12$ per ton of C.

According to Kimaro et al. (2011) soil organic C stocks (within 0–30 cm depth) under 5 years old rotational woodlots (15.8–25.6 Mg C ha^{-1}) in Morogoro, Tanzania, were higher than in soils that had been continuously cropped for the same time period (13 Mg ha^{-1}) and soils under Miombo woodlands (9–15 Mg ha^{-1}).

Many nitrogen fixing trees mainly used for fuelwood in developing countries can ameliorate soil through fixing nitrogen in soil. Some of these include *Leucaena leucocephala* (300–548 kg N ha^{-1} year^{-1}), *Acacia nilotica* (40–-100 kg N ha^{-1} year^{-1}), *Prosopis juliflora* (30–80 kg N ha^{-1} year^{-1}), *Albizia lebbeck* (94 kg N ha^{-1} year^{-1}) *Casuarina equisetifolia* (50–80 kg N ha^{-1} year^{-1}), with an overall average fix of about 60–600 kg N ha^{-1} year^{-1} (Singh et al. 2021). Singh and Gundimeda (2014) assessed the life cycle environmental footprint of all cooking fuels used in India. They assumed a figure of 76% for non-renewability of fuelwood for cooking. However, they reported that if all the firewood was supplied from renewable sources, the global warming potential (GWP) would sharply reduce to 71 kg CO_2 eq/GJ. In one 9-year-old stand (2500 trees per ha) of *Acacia auriculiformis*, belowground and aboveground carbon stock was observed to be 8.9 and 172.0 Mg ha^{-1}, respectively (Kumar et al. 1998). Nair et al. (2009b) reported that soil carbon stock in humid woodlots ranged from 61 to 75 Mg ha^{-1} depending upon maturity age. Sheikh et al. (2015) compared the C storage of two nitrogen-fixing trees in mixed and monospecific plantations to investigate the C sequestration potential after 10 years of their establishment. The study was carried out in three types of plantations, *Dalbergia sissoo* pure, *Leucaena leucocephala* pure and mixed plantation of both. The results indicated that mixed D. plantation sequestered 34.30 ± 0.24 Mg year^{-1} ha^{-1} CO_2 compared to 27.35 ± 0.19 Mg year^{-1} ha^{-1}

CO_2 in *D. sissoo* and 19.81 ± 0.44 Mg year^{-1} ha^{-1} CO_2 in *L. leucocephala*. Total carbon storage was also maximum in mixed plantation (93.47 ± 0.67 Mg ha^{-1}) followed by *D. sissoo* (74.54 ± 0.53 Mg ha^{-1}) and *L. leucocephala* (53.98 ± 1.21 Mg ha^{-1}) showing synergetic effect of plantations and revealing the fact that mixed plantations of N–fixer trees have potential to sequester more carbon than the same species in monoculture.

18.3.5 Multi-Strata Agroforestry

Multi-strata agroforestry systems comprise a variety of land use systems ranging from plantations of commercial crops (e.g. bananas, coffee, cacao, tea, etc.) under shade trees, fruit trees to diversified multi-story home gardens. The home gardens are the most complex of the multi-strata agroforestry practices (Fernandes et al. 1985). Traditional home gardens are the predominant land use types in some parts of India, especially the North Eastern states (Fig. 18.4) like Assam and Tripura, West Bengal and parts of the Andaman and Nicobar Islands, and the Southern states of Kerala and Tamil Nadu (Nath et al. 2021). In Kerala state alone, home gardens cover 1.4 million ha (Kumar 2006). In the Chaga home gardens in Tanzania, intensive mixed intercropping is practiced throughout the year. This involves the integration of several trees with food, cash crops and livestock simultaneously on the same unit of land. On an average sized farm (0.2–1.5 ha) over a hundred different plant species can be found, making this system highly integrated.

18.3.5.1 Adaptation Benefits

The trees bring about a whole complex of environmental changes, affecting light interception, humidity, air temperature, soil temperature, soil moisture content, wind movement, pest and disease complexes. The effects are beneficial in moderating

Fig. 18.4 Left: Multistrata pineapple agroforestry system in North East India, Right: Agroforestry development on shifting cultivated land in North East India

climate variability. In traditional pineapple agroforestry systems, the ethnic farmers deliberately retain large trees, preserve, replant in plantations because of their agronomic, economic or cultural value, especially fast growing and fruit trees for generating cash, timber, fuelwood etc. (Reang et al. 2021). Their study reported shade has a beneficial impact on pineapple growth quality with regard to fruit size, sweetness and fibre content, and the productivity of these systems can directly relate to increased adaptive capacity of the farmers.

18.3.5.2 Mitigation Benefits

For fruit trees using data from Sambane (2005) in Mozambique, we estimated C storage of 114 Mg ha^{-1} CO_2eq in mango block planting (6 m × 6 m spacing) with a rotation period of 60 years. Similarly, for avocado and *Uapaca kirkiana* fruit trees planted at 6 m × 6 m spacing under 20 years rotation, we estimated C storage of 43 Mg ha^{-1} CO_2eq in Malawi. In a mixed 26-year-old mixed stand of cocoa in Cameroon (West Africa), Duguma et al. (2001) reported 20.5 and 145.0 Mg ha^{-1} C stock in belowground and above ground components, respectively sequestering about 3.2 83 Mg C ha^{-1} year^{-1} while in home gardens (13 years stand) the aboveground and belowground carbon stock was 8.8 Mg ha^{-1} and 44.1 Mg ha^{-1}, respectively. Brakas and Aune (2011) reported the standing biomass and carbon accumulation in the smallholder farming systems in the Philippines and the highest rate of C accumulation was found in mango (*Mangifera indica*) plantation (17.9 Mg ha^{-1} year^{-1}) followed by banana + fruit trees (13.6 Mg ha^{-1} year^{-1}). In multi-strata agroforest, home garden, coffee plantation and corn + coffee the accumulation rate was 4.1 Mg ha^{-1} year^{-1}, 9.4 Mg ha^{-1} year^{-1}, 5.3 Mg ha^{-1} year^{-1} and 2.8 Mg ha^{-1} year^{-1}, respectively. Tschora and Cherubini (2020) reported in shaded agroforestry above cocoa, coffee, oil palm and banana in Western Africa sequestered 83.7 7.0 Mg C per ha and stated that the system can sequester 135 metric ton CO_2 per year over two decades corresponding to about 166% of the C emissions from fossil fuels in Western Africa.

In India, the soil carbon sequestration potential (0.5–0.8 Mg C ha^{-1} year^{-1}) of these systems is higher than that of agricultural systems such as rice-paddy and comparable to that of single-species tree-crop systems involving rubber, areca and coconut (Brahma et al. 2017). Similarly, in Ethiopia a higher SOC storage of 158–195 Mg ha^{-1} at a soil depth of 0–60 cm was reported from the home gardens (Betemariyam et al. 2020).

18.3.6 Silvopastoral Systems

In much of Africa, livestock production depends on range grazing in the pastoral and agropastoral areas (Chakeredza et al. 2007). Due to the rapid increase in human population, decrease in grazing land and the increases in livestock numbers, the rangelands are overstocked and are being overgrazed (Holechek et al. 2017). Therefore, pastoralists and smallholder farmers face major problems of fodder shortage especially during the dry season. Animals are usually fed on poor quality roughages derived largely from cereal crop residues. Climate change will have significant negative impacts on livestock production systems particularly in the drier rangeland systems (Thornton and Herrero 2010). While livestock production is an important tool for adaptation (Weindl et al. 2015), it is also a large contributor (up to 18%) of global anthropogenic GHG) emissions (Thornton and Herrero 2010).

18.3.6.1 Adaptation Benefits

Utilization of trees and shrubs have been recognized to be one of the most effective means of improving both the supply and quality of forage in tropical smallholder systems, especially during the dry season (Chakeredza et al. 2007). Green fodder from nitrogen-fixing legumes contains much higher protein levels than poor quality (basal feeds of grasses and crop residues such as stover) available during the dry season. According to Thornton and Herrero (2010) replacing some concentrates and part of the basal diet with leaves of agroforestry species such as *Leucaena leucocephala* can intensifies diets so that animal numbers can be reduced while still meeting livestock product demand.

Fodder banks involve planting leguminous trees and shrubs with high nutritive value on crop land, along boundaries, pathways or across contours to curb soil erosion. Fodder banks have been widely tested in Tanzania, Malawi and Zimbabwe particularly under the smallholder dairy sector (Chakeredza et al. 2007). The fodder shrubs are harvested periodically during the growing season and used either as a supplement or a substitute to the more expensive dairy concentrate. The fodder can be used for controlled browsing or feeding to animals in an enclosure in a cut-and carry fashion. This has been shown to result in significant increases in milk and meat yield.

Consistently higher N and P concentrations have also been reported for manure from cattle fed on protein-rich fodder (Sileshi et al. 2017), and application of such manure to staple crops can increase yields. This has implications for adaptation to climate change. Planting fertilizer trees can also tighten N cycling in the cropping system, increase carbon sequestration, reduce the need for fertilizer N inputs (Sileshi et al. 2014a, b), and potentially lower GHG emissions (see Mitigation).

In India, silvopastoral agroforestry is more predominant on degraded lands, particularly on ravine lands and salt-affected soils. On highly sodic soils the system can provide significant amounts of timber and fuelwood, which improve local well-being by providing small timber and fuelwood on marginal lands. In one study of *Acacia nilotica* + *Desmostachya bipinnata*, *Dalbergia sissoo* + *D. bipinnata*, and *Prosopis juliflora* + *D. bipinnata*, the bole wood that can be used as timber was 4.62–9.78 Mg ha^{-1}, and branch biomass production varied between 4.16 and 20.82 Mg ha^{-1} $year^{-1}$ (Kaur et al. 2002a). Timber and fuelwood biomass in clonal *Eucalyptus tereticornis* plantation in different spacing showed timber production of

13.5–141.7 Mg ha^{-1} in shallow water table areas (Dagar et al. 2016a, b). *Salvadora persica*-based silvopastoral system was developed with forage grasses (*Leptochloa fusca, Eragrostis* sp., and *Dichanthium annulatum*) on clay loam saline Vertisols (ECe being 25–70 dS m^{-1}) in Gujarat (Rao Gururaja et al. 2003). *Leptochloa fusca, Eragrostis* sp., and *Dichanthium annulatum*, when planted on 45 cm high ridges, could produce 3.17, 1.85, and 1.09 Mg ha^{-1} forage, respectively. When planted in furrows, the forage yield was 3.75, 1.76, and 0.54 Mg ha^{-1} in the case of *Leptochloa fusca, Eragrostis* sp., and *Dichanthium annulatum*, respectively, showing their potential for these highly degraded lands. These grasses absorbed and accumulated large quantity of salt in their biomass which resulted in amelioration of the soil to great extent by reducing the pH and ECe values of the soil. The litter accumulation on the ground floor in the two systems was, i.e., *Salvadora persica* system (2.712 $\pm$ 0.154 to 3.682 $\pm$ 0.136 Mg ha^{-1}) and *Acacia nilotica* system (2.216 $\pm$ 128 to 2.442 $\pm$ 0.135 Mg ha^{-1}). The carbon content in ground floor litter ranged from 1.108 to 1.841 Mg C ha^{-1} being greater in the case of *Salvadora* system. In salt-affected soils, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land-use type and tree species. It was interesting to find a significant relationship between microbial biomass carbon and plant biomass carbon ($r = 0.92$) as well as the flux of carbon in net primary productivity ($r = 0.92$). Nitrogen mineralization rates were found greater in silvopastoral systems compared to sole grass system. Soil organic matter was positively correlated with microbial biomass carbon, soil nitrogen, and nitrogen mineralization rates ($r = 0.95$–0.98, $p < 0.01$) (Kaur et al. 2002b).

In India, the studies on biomass production from natural grassland and silvopastoral system comprising *Albizia amara, Dichrostachys cinerea* and *Leucaena leucocephala* as woody perennials with *Chrysopogan fulvus* as grass and *Stylosanthes hamata* and *S. scabra* as legume in dry climate revealed that in 8 years, rate of biomass carbon stored in silvopastoral system was 6.72 Mg C ha^{-1} $year^{-1}$, two times more than 3.14 Mg C ha^{-1} $year^{-1}$ from natural grassland (NRCAF 2007). Rai et al. (2009) studied the effect of introducing a silvopastoral system in a natural grassland in semi-arid Indo-Gangetic region, where introduced species of *Albizia procera, Eucalyptus tereticornis, Albizia lebbeck, Embilica officinalis* and *Dalbergia sissoo* accumulated 8.6, 6.92, 6.52, 6.25 and 5.41 Mg ha^{-1} $year^{-1}$ of biomass. Here, the carbon storage in the system was 1.89 to 3.45 Mg Cha^{-1} $year^{-1}$ in silvopasture and 3.94 Mg Cha^{-1} $year^{-1}$ in pure protected pasture.

18.3.6.2 Mitigation Benefits

The use of agroforestry practices such as fodder banks in mixed crop-livestock systems can have dual mitigation benefits, namely reducing methane (CH_4) emissions and increased carbon sequestration. Enteric CH_4 is a greenhouse gas that causes significant loses of energy in ruminants and contributes to greenhouse warming (Hristov et al. 2013). So, in targeting CH_4 reduction it is critical to develop a strategy that decrease methane producing microbiota activities and proliferation without limiting rumen functions. Tree legumes also contain variable amounts of tannins. Recently a number of reports have shown reduction of enteric CH_4 production due to inclusion of tannin rich browse because these tannins have anti-methagenic activity, either by direct inhibition of methanogens or indirectly through inhibition of protozoa (Hristov et al. 2013; Patra and Saxena 2011). Tannins are polyphenolic compounds which bind protein and can protect and decrease rumen fermentation of proteins in a feed (Makkar 2003). Tannins from different plants might show different response in digestibility and methane production. Fodder trees such *Calliandra callothyrsus* and *Leucaena* species have shown to reduce methanogenesis per unit of organic matter fermented. Therefore, tannin-reach legumes such as Calliandra can be used in combination with good quality forage species to reduce methane emission from rumen fermentation. Most studies on this were conducted in vitro. There is a need for more in-vivo studies that allow the quantification of whole-body methane emission and protein and energy utilization.

Ruminant diets that are higher in quality also result in reduced methane output per unit of milk and meat as well as in higher meat and milk productivity. For example, adding even a small amount of Leucaena leaves to dairy cattle can treble milk yield per day, quadruple weight gain per day, thereby increasing farm income considerably, and reduce the amount of methane produced per kg of meat and milk by factors of 2 and 4, respectively (Thornton and Herrero 2010). Intensification diets could also considerably reduce the number of animals needed to satisfy demand for milk and meat, and consequently reduce CH_4 emissions. The trees also accumulate considerable C in biomass (Table 18.3) and hence offer greater opportunities for mitigation. According to analyses by Thornton and Herrero (2010), about 28% of the plausible mitigation potential of *Leucaena* fodder banks comes from the reduction in livestock numbers (due to diet intensification) compared with 72% contributed from the carbon sequestration effects of trees.

Elijah et al. (2021) simulated CH_4 emission levels from different dairy feeding strategies in Western Kenya. Ms. had a mean of 0. 813 CO_2-eq against 0. 608 CO_2-eq for Napier and 0.611 CO_2-eq for legume fodder and grain supplemented strategies. Though the highest CH4 mitigation effect in the dairy feeding strategies from external inputs such as CSC are evident, the effect on CH_4 is not significantly different ($p \leq 0.05$) from farm grown legume fodder such *as Luceana* and *Sesbania.* In effect, farm produced legume fodder including dairy-agroforestry integrated systems could be as effective in the mitigation of CH_4 emissions from ruminants (Elijah et al. 2021).

The enhanced use efficiency of rain water by woody species can also improve productivity of silvopastoral systems. In a study in arid region, Roy et al. (2011) found that in *Acacia tortilis*-based silvopasture system, canopy interception was 21.4%, whereas in *Colophospermum mopane*-based silvopasture system it was 13.1% and the average surface runoff in first system was 53% higher than the second system. This indicated that hydraulic response to rain is dominated by plant species character; however, the per cent annual runoff and soil erosion were very low in situations with trees on agricultural fields in comparison to bare soil condition.

18.4 Policies Incentive Mechanisms

Globally, policy response to climate change has mainly been through adaptation and mitigation strategies. Agroforestry can connect the climate change policy imperatives on mitigation and adaptation: reducing human vulnerability to increased climate variability and global warming trends (Duguma et al. 2014). Therefore, inclusion of interventions such as traditional farmers' knowledge into formal climate change mitigation and adaptation strategies will be a viable way to reduce exposure and enhance adaptation by increasing the adaptive capacity of the communities managing the agroforestry systems. This is important because local conditions determine vulnerability and adaptive capacity. However, enabling policy environments are needed to address many of the challenges including land and tree tenure and carbon rights to spur investment in agroforestry many countries. Over the past several decades, agroforestry science has gone from biophysical research to understanding the agroforestry policy domain and how to bridge the policy gap between agriculture and forestry policies (Van Noordwijk 2019). Nevertheless, very few countries have policies promoting agroforestry alone or as part of their Nationally Determined Contributions (NDCs) to the UNFCCC (see Chap. 19 by Duguma et al. in this book). One of the prime examples is India, a strong national agroforestry policy exists to support smallholder farmers (Chavan et al. 2015).

Global, national, and local incentive mechanisms are used in many agriculture and forestry initiatives to promote wider adoption of certain technologies (Catacutan et al. 2012; Setti et al. 2019). An incentive may be defined as something that serves as motivation to accomplish a task, which may lead to rewards. In many countries, such incentives are lacking for farmers to adopt agroforestry although the global carbon market has opened new opportunities through which smallholders can benefit from carbon trading. Even in countries where such incentives exist, smallholders hardly benefit from them due to lack of information and resources to leverage policy implementation (Catacutan et al. 2012). Promotion of economic instruments such as Payment for Environmental Services can encourage voluntary practices such as agroforestry (Setti et al. 2019). Catacutan et al. (2012) recommended that national institutions should catalyse international carbon incentives for smallholders, while local governments should be primed to address smallholder needs through locally designed incentive mechanisms. The need for improved land and tree tenure and security has also been emphasized in a number of studies (Djalilov et al. 2016).

An integrated approach embracing agroforestry as an agroecological solution for sustainable food production, attain higher resilience to climate variability and change (Fig. 18.5). In that regard, we strongly recommend development of policy instruments that clarify land and tree tenure and carbon rights to motivate local stakeholders to implement agroforestry. Adoption of national agroforestry strategies and guidelines can also bridge the agriculture and forestry policy divide (ASEAN 2018), and spur investment by the private sector as well as incentivize farmers and rural communities to engage in tree planting. To facilitate agroforestry development and help bridge the gap between agriculture and forestry policy spheres, countries could

Fig. 18.5 An integrated approach for achieving climate-smart agroforestry

develop Guidelines for Agroforestry Development following the example from Southeast Asia (ASEAN 2018).

18.5 Knowledge Gaps and Areas for Future Research

Although recent synthesis and meta-analysis have increased our knowledge about soil carbon in agroforestry (e.g. Chatterjee et al. 2018; Corbeels et al. 2019; Das et al. 2022; Hübner et al. 2021; Nath et al. 2021; Shi et al. 2018), there is still a great deal of uncertainty. Soil organic matter needs to be understood in its central role in belowground C storage (mitigation) and its influence on soil water balance and hence on climate vulnerability (adaptation) (Gusli et al. 2020). Information on all aboveground and belowground inputs and their associated turnover rates and interaction with mineral soil particles in shaping soil physical properties might advance our understanding of the factors controlling the SOC dynamics under the agroforestry systems. Changes in SOC storage over time can indicate the net effects of interacting processes, as both plants and farmers adapt to climate change (Van Noordwijk et al. 2014). Co-adaptation of people and trees is needed for resilience to climate change in the medium term (Van Noordwijk et al. 2011).

The adaptation and mitigation potentials of agroforestry has attracted significant interest in carbon credits under Verified Carbon Standards and Reduced Emissions from Deforestation and Forest Degradation (REDD) programs. The green bonds issued by the World Bank also offer opportunities for agroforestry interventions to benefit local people to contribute to mitigation as well as adaption to climate change. Recent analyses conducted in Australia (Wise and Cacho 2005) and Peru (Antle et al. 2007) have shown that agroforestry systems are profitable at certain levels of carbon prices. All sources of climate finance demand evidence of mitigation benefits. However, verifying mitigation is technically challenging because direct measurement of carbon stored in tree biomass and soil across widely dispersed smallholder farms is costly and faces large uncertainty. There is an urgent need for a cost-effective framework for monitoring, reporting and verification across the range of agroforestry technologies.

Another major challenge has been implementing agroforestry interventions at a wider scale to benefit millions of farmers. Key among the constraints is lack of high-quality planting material well adapted to specific conditions and lack of knowledge on optimum tree-crop spatial arrangements and tree stocking densities. In agroforestry arrangements, stocking densities and management can significantly influence tree growth, biomass accumulation and system carbon storage. For example, in Malawi, large *Faidherbia* trees in parklands stored roughly 20 times as much total above-ground biomass as large trees in block planting (Beedy et al. 2016). Although the parklands had larger biomass per tree compared to the block planting, the block planting stored more biomass per unit area due to the high stocking density. The difference in tree biomass between the two regimes can be attributed to difference in tree architecture; trees growing under high stocking densities are often taller with smaller crowns and fewer twigs which translate into lower total aboveground biomass on individual tree basis (Beedy et al. 2016). Recent modelling exercises (Sileshi et al. 2014b) show that high stocking densities can slow down growth and increment in stem diameter in *Faidherbia*. High initial stocking densities of > 625 plants ha^{-1} leads to rapid self-thinning, while low initial densities (< 100 plants ha^{-1}) can result in sub-optimal use of site resources and delayed net ecosystem production (Sileshi et al. 2014b). As a compromise, block planting of *Faidherbia* with initial densities of about 625 trees ha^{-1} planted in 4 m $\times$ 4 m spacing, progressive thinning and maintaining stocking densities below 70 plants ha^{-1} when stem diameter exceeds 25 cm. A density of 10 trees/ha is considered optimal to support crop productivity in *F. albida* parklands (Roupsard et al. 2020). This kind of information is lacking for most species. Therefore, future research should focus on identifying other species and site-specific management practices including stocking densities, pruning regimes and spatial arrangements that optimize crop productivity and carbon sequestration.

In some areas tree planting with exotic species may be more challenging due to cultural or biophysical barriers. In those situations, identifying locally adapted trees and encouraging greater natural regeneration may achieve the desired tree stocking density and C accumulation faster than block planting. This requires increased research in regeneration ecology.

As indicated in Sect. 18.4, many countries do not have policies and incentive mechanisms supportive of agroforestry. Therefore, empirical research and policy analyses are needed for governments to devise evidence-based guidelines and policies. There is also a need for commissioning regional-level assessments of climate change impacts, vulnerabilities and adaptation options involving the agroforestry managers. This will lead to improved and more targeted information that can guide development of evidence-based policies.

18.6 Conclusions and Recommendation

From the review above it can be concluded that agroforestry practices provide productivity, adaptation and mitigation benefits. Through their impact on microclimate and improvement in water use efficiency agroforestry trees can make crop production systems more resilient. Available evidence also suggests that widespread adoption of agroforestry in crop and livestock production systems can offer substantial mitigation potential. Agroforestry can also have an indirect effect on carbon sequestration when it helps decrease pressure on forests, which are the natural sinks of terrestrial carbon.

References

Agroforestry Network (2019) Agroforestry for adaptation and mitigation to climate change. www.agroforestrynetwork.org

Akinnifesi FK, Ajayi OC, Sileshi G, Chirwa PW, Chianu J (2010) Fertilizer trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron Sustain Dev 30:615–619

Aldy JE, Pizer WA (2015) Alternative metrics for comparing domestic climate change mitigation efforts and the emerging international climate policy architecture. Rev Environ Econ Policy 10(1). https://doi.org/10.1093/reep/rev013

Antle JM, Stoorvogel JJ, Valdivia RO (2007) Assessing the economic impacts of agricultural carbon sequestration: Terraces and agroforestry in the Peruvian Andes. Agric Ecosyst Environ 122:435–445

Arora S, Dagar JC (2019) Salinity tolerance indicators. In: Dagar JC, Yadav RK, Sharma PC (eds) Research developments in saline agriculture. Springer, Singapore, pp 155–201

ASEAN (Association of Southeast Asian Nations) (2018) ASEAN guidelines for agroforestry development. ASEAN Secretariat, Jakarta

Assogbadjo AE, Kakaï R, Vodouhê FG, Djagoun CS, Codjia JTC, Sinsin B (2012) Biodiversity and socioeconomic factors supporting farmers' choice of wild edible trees in the agroforestry systems of Benin (West Africa). For Policy Econ 14:41–49

Bado BV, Whitbread A, Laminou M, Manzo S (2020) Improving agricultural productivity using agroforestry systems: Performance of millet, cowpea, and *Ziziphus*-based cropping systems in West Africa Sahel. Agric Ecosys Environ. https://doi.org/10.1016/j.agee.2020.107175

Banerjee H, Dhara PK (2011) Evaluation of different agri-horti-silvicultural models for rainfed uplands in West Bengal. Prog Agric 11(1):143–148

Barker R, Molle F (2004) Evolution of irrigation in South and Southeast Asia. Comprehensive Assessment Secretariat. (Comprehensive Assessment Research Report 5), Colombo

Barrios E, Sileshi G, Shepherd K, Sinclair FL (2012) Agroforestry and soil health: linking trees, soil biota and ecosystem services. In: Wall DH (ed) The Oxford handbook of soil ecology and ecosystem services. Oxford University Press, Oxford, pp 315–330

Bartholomé E, Belward AS (2005) A new approach to global land cover mapping from Earth observation data. Int J Remote Sens 26:1959–1977

Beedy TL, Snapp SS, Akinnifesi FK, Sileshi GW (2010) Impact of *Gliricidiasepium* intercropping on soil organic matter fractions in a maize-based cropping system. Agric Ecosyst Environ 138: 139–146

Beedy TL, Chanyenga TF, Akinnifesi FK, Sileshi GW, Nyoka BI, Gebrekirstos A (2016) Allometric equations for estimating above-ground biomass and carbon stock in *Faidherbia albida* under contrasting management in Malawi. Agrofor Syst 90:1061–1076

Belsky AJ (1994) Influences of trees on savannah productivity: test of shade, nutrients, and tree-grass competition. Ecology 75:922–932

Betemariyam M, Negash M, Worku A (2020) Comparative analysis of carbon stocks in home garden and adjacent coffee-based agroforestry Systems in Ethiopia. Small-Scale For 19:319–334. https://doi.org/10.1007/s11842-020-09439

Binam JN, Place F, Kalinganire A, Hamade S, Boureima M, Tougiani A, Dakouo J, Mounkoro B, Diaminatou S, Badji M, Diop M, Babou AB, Haglund E (2015) Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa. Environ Econ Policy Stud 17:543–575

Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1:234–239

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa. FAO Conservation Guide 34. Food and Agriculture Organization, Rome

Brahma B, Pathak K, Lal R, Kurmi B, Das M, Nath PC, Nath AJ, Das AK (2017) Ecosystem carbon sequestration through restoration of degraded lands in north East India. Land Degrad Dev. https://doi.org/10.1002/ldr.2816

Brakas SG, Aune JB (2011) Biomass and carbon accumulation in land use systems of Claveria, The Philippines. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems: opportunities and challenges. Advances in agroforestry, vol 8. Springer, Dordrecht, pp 163–175

Campbell BM, Thornton P, Zougmoré R, van Asten P, Lipper L (2014) Sustainable intensification: what is its role in climate smart agriculture? Curr Opin Environ Sustain 8:39–43

Castaldi S, Ermice A, Strumia S (2006) Fluxes of N_2O and CH_4 from soils of savannas and seasonally-dry ecosystems. J Biogeogr 33:401–415

Catacutan DC, Lasco RD, Piñon CD (2012) Incentive mechanisms for smallholder agroforestry: opportunities and challenges in the Philippines. In: Nair PK, Garrity D (eds) Agroforestry—the future of global land use. Advances in agroforestry, vol 9. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4676-3_24

Chakeredza S, Hove L, Akinnifesi FA, Franzel S, Ajayi O, Sileshi G (2007) Managing fodder trees as a solution to human-livestock food conflicts and their contribution to income generation for smallholder farmers in Southern Africa. Nat Resour Forum 31:286–291

Charbonnier F, le Maire G, Dreyer E, Casanoves F, Christina M, Dauzat J, Eitel JU, Vaast P, Vierling LA, Roupsard O (2013) Competition for light in heterogeneous canopies: application of MAESTRA to a coffee (*Coffea arabica* L.) agroforestry system. Agric For Meteorol 181: 152–169

Chatterjee N, Nair PKR, Chakraborty S, Nair VD (2018) Changes in soil carbon stocks across the forest-agroforest-agriculture/pasture continuum in various agroecological regions: a meta-analysis. Agric Ecosyst Environ 266:55–67

Chavan SB, Keerthika A, Dhyani SK, Handa AK, Newaj R, Rajarajan K (2015) National agroforestry policy in India: a low hanging fruit. Curr Sci 108(10):1826–1834. https://doi.org/10.18520/cs/v108/i10/1826-1834

Coleman DC, Edwards AL, Belsky AJ, Mwonga S (1991) The distribution and abundance of soil nematodes in East African savannas. Biol Fertil Soils 12:67–72

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res 188:16–26

Coulibaly JY, Mbow S, Sileshi GW, Beedy TL, Kundhlande G, Musau J (2015) Mapping vulnerability to climate change in Malawi: Spatial and social differentiation in the Shire River basin. Am J Climate Change 4:282–294

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services. Advances in agroforestry, vol 10. Springer, New York, pp 273–332

Dagar JC, Minhas PS (2016) Agroforestry to rehabilitate the Indian coastal saline areas. In: Dagar JC, Minhas PS (eds) Agroforestry for management of waterlogged saline soils and poor-quality waters. Advances in agroforestry, vol 13. Springer, Dordrecht, pp 121–143

Dagar JC, Tewari VP (2017) Evolution of agroforestry as modern science. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 13–90

Dagar JC, Singh G, Singh NT (2001) Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali soils in India. Arid Land Res Manag 15:115–133

Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services. Advances in agroforestry, vol 10, pp 185–232

Dagar JC, Lal K, Ram J, Kumar M, Chaudhari SK, Yadav RK, Ahamad S, Singh G, Amarinder K (2016a) Eucalyptus geometery in agroforestry on waterlogged saline soils influences plant and soil traits in north-West India. Agric Ecosyst Environ 233:33–42

Dagar JC, Yadav RK, Tomar OS, Minhas PS, Gajender Y, Lal K (2016b) Fruit-based agroforestry systems for saline water irrigated semi-arid hyperthermic camborthids soils of north-west India. Agrofor Syst 90(6):1123–1132

Dagar JC, Gangaiah B, Gupta SR (2020) Agroforestry to sustain island and coastal agriculture in the scenario of climate change: Indian perspective. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and challenges, vol 1. Springer, Singapore, pp 367–424

Das S, Chatterjee S, Rajbanshi J (2022) Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: A meta-analysis. Sci Total Environ 805:150428. https://doi.org/10.1016/j.scitotenv.2021.150428

Dhyani SK, Ram A, Dev I (2016) Potential of agroforestry systems in carbon sequestration in India. Indian J Agr Sci 86:1103–1112

Dierks J, Blaser-Hart WJ, Gamper HA, Six J (2021) Mycorrhizal fungi-mediated uptake of tree-derived nitrogen by maize in smallholder farms. Nat Sustain. https://doi.org/10.1038/s41893-021-00791-7

Dilla AM, Smethurst PJ, Huth NI, Barry KM (2020) Plot-scale agroforestry modeling explores tree pruning and fertilizer interactions for maize production in a Faidherbia parkland. Forests 11: 1175. https://doi.org/10.3390/f11111175

Djalilov BM, Khamzina A, Hornidge AK, Lamers JPA (2016) Exploring constraints and incentives for the adoption of agroforestry practices on degraded cropland in Uzbekistan. J Environ Plan Manag 59(1):142–162. https://doi.org/10.1080/09640568.2014.996283

Droppelmann KJ, Lehmann J, Ephrath J, Berliner PR (2000) Water use efficiency and uptake patterns in a run off agroforestry system in an arid environment. Agrofor Syst 49:223–243

Duarte EMG, Cardoso IM, Stijnen T, Mendonça MAFC, Coelho MS, Cantarutti RB, Kuyper TW, Villani EMA, Mendonça ES (2013) Decomposition and nutrient release in leaves of Atlantic rainforest tree species used in agroforestry systems. Agrofor Syst 87(4):835–847

Duguma B, Gockowski J, Bakala J (2001) Smallholder cacao (*Theobroma cacao* Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. Agrofor Syst 51:177–188

Duguma LA, Minang PA, Van Noordwijk M (2014) Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. Environ Manag 54:420–432

Dutaur L, Verchot LV (2007) A global inventory of the soil CH_4 sink. Global Biogeochemical Cycles 21: GB4013

Elijah TV, Makungo R, Ekosse G-I (2021) Effective mainstreaming of agricultural emissions into climate action agenda: the case of institutions and smallholder dairy production systems, Western Kenya. Atmosphere 12:1507. https://doi.org/10.3390/atmos12111507

FAO (2013) Climate smart agriculture sourcebook. Food and Agriculture Organisation of the United Nations, Rome. http://www.fao.org/docrep/018/i3325e/i3325e04.pdf

FAO (2015) Climate change mitigation and smallholder agriculture in Zambia. EPIC (Economics and Policy Innovations for Climate-Smart Agriculture). Policy Brief No.3, FAO, Rome

FCCC (2012) Slow onset events-technical paper, FCCC/TP/2012/7. Framework Convention on Climate Change, United Nations

Fernandes ECM, Oktingati A, Maghembe J (1985) The Chagga homegardens: a multistoried agroforestry cropping system on Mt. Kilimanjaro (Northern Tanzania). Agrofor Syst 2:73–86

Gera M, Mohan G, Bisht NS, Gera N (2006) Carbon sequesatrtion potential under agroforestry in Rupnagar district of Punjab. Indian For 132:543–555

Girvetz E, Villegas JR, Claessens L, Lamanna C, Navarro-Racines C, Nowak A, Thornton P, Rosenstock TS (2019) Future climate projections in Africa: where are we headed? In: Rosenstock TS et al (eds) The climate-smart agriculture papers. Springer, Cham, pp 15–27. https://doi.org/10.1007/978-3-319-92798-5_2

Grewal SS, Lohan HS, Dagar JC (2021) Micro-irrigation in drought and salinity prone areas of Haryana: socio-economic impacts. J Soil Salin Water Qual 13(1):94–108

Gusli S, Sumeni S, Sabodin R, Muqfi IH, Nur M, Hairiah K, Useng D, van Noordwijk M (2020) Soil organic matter, mitigation of and adaptation to climate change in cocoa–based agroforestry systems. Land 9:323. https://doi.org/10.3390/land9090323

Haishui Z, Kejun H (1991) Intercropping in rubber plantation and its economic benefits. In: Zhaohua Z, Mantang C, Shiji W, Youxu J (eds) Agroforestry in China. Chinese Academy of Forestry Republic of China and International Development Research Centre Canada, Singapore, pp 204–206

Hatfield JL, Sauer TJ, Prueger JH (2001) Managing soils to achieve greater water use efficiency: a review. Agron J 93:271–280

Heink U, Kowarik I (2010) What are indicators? On the definition of indicators in ecology and environmental planning. Ecol Indic 10:584–593

Hijioka YE, Lin JJ, Pereira RT, Corlett X, Cui GE, Insarov RD, Lasco E, Lindgren SA (2014) Asia. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PK, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1327–1370

Hluyako LL, Odindo AO, Mafongoya P, Sithole NJ, Magwaza LS (2017) Characterisation of pigeon pea (*Cajanus cajan*) landraces grown in two climatic zones in KwaZulu-Natal province, South Africa. S Afr J Plant Soil 34:191–199

Holechek JL, Cibils AF, Bengaly K, Kinyamario JL (2017) Human population growth, African pastoralism, and rangelands. Rangel Ecol Manag 70:273–280
Hristov AN, Oh C, Lee J, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Dijkstra J, Oosting S (2013) Mitigation of greenhouse gas emissions in livestock production—a review of technical options for non-CO_2 emissions. FAO Animal Production and Health Paper No. 177 (Ed.P.J. Gerber,B.Henderson and H.P.S Makkar).FAO, Rome Italy
Huang W, Kanninen M, Xu O, Huang B (1997) Agroforestry in China: present state and future potential. Ambio 26(6):394–398
Hübner R, Kühnel A, Lu J, Dettmann H, Wang W, Wiesmeier M (2021) Soil carbon sequestration by agroforestry systems in China: a meta-analysis. Agric Ecosys Environ 315. https://doi.org/10.1016/j.agee.2021.107437
Huxman TE, Smith MD, Fay PA, Knapp AK, Shaw MR, Loik ME, Smith SD, Tissue DT, Zak JC, Weltzin JF, Pockman WT, Sala OE, Haddad BM, Harte J, Koch GW, Schwinning S, Small EE, Williams DG (2004) Convergence across biomes to a common rain-use efficiency. Nature 429: 651–654
IPCC (2007a) Intergovernmental Panel on Climate Change (IPCC). Fourth assessment report: climate change, Geneva
IPCC (2007b) Summary for policymakers. Climate change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge
IPCC (2007c) Climate change: Climate change impacts, adaptation and vulnerability, summary for policymakers. Intergovernmental Panel on Climate Change
IPCC (2021) Climate Change 2021—the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press
Jat ML, Dagar JC, Sapkota TB, Yadvinder-Singh GB, Ridaura SL, Saharawat YS, Sharma RK, Tetarwal JP, Hobbs H, Stirling C (2016) Climate change and agriculture: adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. Adv Agron 137: 1–115
Jat HS, Choudhary KM, Nandal DP, Yadav AK, Poonia T, Singh Y, Sharma PC, Jat ML (2020) Conservation agriculture-based sustainable intensification of cereal systems leads to energy conservation, higher productivity and farm profitability. Environ Manag 65(6):774–786
Jose S, Gillespie AR, Pallardy SG (2004) Interspecific interactions in temperate agroforestry. Agrofor Syst 61:237–255
Kalita RM, Das AD, Sileshi GW, Nath AJ (2020) Ecosystem carbon stocks in different aged tea agroforestry systems: implications for regional ecosystem management. Trop Ecol 61:203–214. https://doi.org/10.1007/s42965-020-00084-8
Kamanga BCG, Kanyama-Phiri GY, Minae S (1999) Intercropping perennial legumes for green manure additions to maize in southern Malawi. Afr Crop Sci J 7:355–363
Kamanga BCG, Waddington SR, Robertson MJ, Giller KE (2010) Risk analysis of maize-legume crop combinations with smallholder farmers varying in resource endowment in central Malawi. Exp Agric 46:1–21
Kaonga M, Bayliss-Smith T (2009) Carbon pools in tree biomass and the soil in improved fallows in eastern Zambia. Agrofor Syst 76:37–51
Kaur B, Gupta SR, Singh G (2002a) Bioamelioration of a sodic soil by silvopastoral system in northwestern India. Agrofor Syst 54:13–20
Kaur B, Gupta SR, Singh (2002b) Carbon storage and nitrogen cycling in slivi-pastoral systems on a sodic soil in northwestern India. Agrofor Syst 54:21–29
Kim D-G (2012) Estimation of net gain of soil carbon in a nitrogen-fixing tree and crop intercropping system in sub-Saharan Africa: results from re-examining a study. Agrofor Syst 86:175–184

Kim D-G, Kirschbaum MUF, Beedy TL (2016) Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: synthesizing available data and suggestions for future studies. Agric Ecosyst Environ 226:65–78

Kimaro AA, Timmer VR, Mugasha AG, Chamshama SAO, Kimaro DA (2007) Nutrient use efficiency and biomass production of tree species for rotational woodlot systems in semi-arid Morogoro, Tanzania. Agrofor Syst 71:175–184

Kimaro AA, Isaac ME, Chamshame SAO (2011) Carbon pools in tree biomass and soils under rotational woodlot systems in Eastern Tanzania. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems. Springer, Dorderecht, pp 129–143

Kimaro AA, Sererya OG, Matata P, Uckert G, Hafner J, Graef F, Sieber S, Rosenstock TS (2019) Understanding the multidimensionality of climate-smartness: examples from agroforestry in Tanzania. In: Rosenstock TS, Nowak A, Girvetz E (eds) The climate-smart agriculture papers, pp 153–162. https://doi.org/10.1007/978-3-319-92798-5_13

Kohli A, Saini BC (2003) Microclimate modification and response of wheat planted under trees in a fan design in northern India. Agrofor Syst 58:109–118

Kumar BM (2006) Carbon sequestration potential of tropical homegardens. In: Tropical homegardens. Springer, pp 185–204

Kumar BM (2011) Species richness and aboveground carbon stocks in the homegardens of central Kerala, India. Agric Ecosyst Environ 140:430–440

Kumar BM, Nair PKR (eds) (2011) Carbon sequestration in agroforestry systems. Springer, Dorderecht, p 307

Kumar BM, Takeuchi K (2009) Agroforestry in the Western Ghats of Peninsular India and the Satoyama landscapes of Japan: a comparison of two sustainable land use systems. Sustain Sci 4: 215–232

Kumar BM, George SJ, Jamaludheen V, Suresh TK (1998) Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in wood lot and silvopastoral experiments in Kerala, India. For Ecol Manage 112:145–163

Kumar V, Jat HS, Sharma PC, Singh B, Gathala MK, Malik RK, Kamboj BR, Yadav AK, Ladha JK, Raman A, Sharma DK, McDonald A (2018) Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric Ecosys Env 252:132–147

Kuntashula E, Mungatana E (2013) Estimating the causal effect of improved fallows on farmer welfare using robust identification strategies in Chongwe—Zambia. Agrofor Syst 87:1229–1246

Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Oborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron Sustain Dev 39(5):1–18. https://doi.org/10.1007/s13593-019-0589-8

Lal R (2015a) Restoring soil quality to mitigate soil degradation. Sustainability 7:5875–5895

Lal P (2015b) Clonal plantation in India: historical perspective and future potential. In: Dhyani SK, Newaj R, Alam B, Dev I (eds) Agroforestry—present status and way forward. Biotech Books, New Delhi, pp 121–134

Leakey RRB (2010) Agroforestry: a delivery mechanism for multi-functional agriculture. In: Kellimore LR (ed) Handbook on agroforestry: management practices and environmental impact. Environmental science, engineering and technology series. Nova Science Publishers, Hauppauge, pp 461–471

Lee Y, Paek J, Park JS, Boo K-O (2020) Changes in temperature and rainfall extremes across East Asia in the CMIP5 ensemble. Theor Appl Climatol 141:143–155

Leroux L, Faye NF, Jahel C, Falconnier GN, Diouf AA, Ndao B, Tiaw I, Senghor HY, Kanfany G, Balde A, Dieye M, Sirdey N, Loison SA, Corbeels M, Baudron F, Bouquet E (2022) Exploring the agricultural landscape diversity-food security nexus: an analysis in two contrasted parklands of Central Senegal. Agric Syst 196:103312. https://doi.org/10.1016/j.agsy.2021.103312

Livesley SJ, Gregory PJ, Buresh RJ (2004) Competition in tree row agroforestry systems. Soil water distribution and dynamics. Plant Soil 246:129–139
Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agron Sustain Dev 34:443–454
Luedeling E, Sileshi G, Beedy T, Dietz J (2011) Carbon sequestration potential by agroforestry in Africa. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems. Springer, Dordrecht, pp 61–83
Mafongoya PL, Sileshi GW (2020) Indices to identify and quantify ecosystem services in sustainable food systems. In: Rusinamodzi L (ed) The role of ecosystem services in sustainable food systems. Elsevier Inc., pp 43–71. https://doi.org/10.1016/B978-0-12-816436-5.00003-2
Makkar HPS (2003) Quantification of tannins in tree and shrub foliage. A laboratory manual. Kluwer Academic Publishers, Dordrecht
Makumba W, Janssen B, Oenema O, Akinnifesi FK, Mweta D, Kwesiga F (2006) The long-term effects of a gliricidia-maize intercropping system in Southern Malawi, on Gliricidia and maize yields, and soil properties. Agric Ecosyst Environ 116:85–92
McKinsey Global Institute (2020) Climate risk and responses: physical hazards and socioeconomic impacts. Full report January, 2020. McKinsey Global Institute
Miller DC, Muñoz-Mora JC, Christiaensen L (2017) Prevalence, economic contribution, and determinants of trees on farms across sub-Saharan Africa. For Policy Econ 84:47–61
Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen ZS, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockmann U, Sulaeman Y, Tsui C-C, Vågen T-G, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. Geoderma 292:59–86
Molua EL (2005) The economics of tropical agroforestry systems: the case of agroforestry farms in Cameroon. For Policy Econ 7:199–211
Monteith JL, Ong CK, Corlett JE (1991) Microclimatic interactions in agroforestry systems. For Ecol Manag 45:31–44
Mortimer PE, Gui H, Xu J, Zhang C, Barrios E, Hyde KD (2015) Alder trees enhance crop productivity and soil microbial biomass in tea plantations. Appl Soil Ecol 96:25–32. https://doi.org/10.1016/j.apsoil.2015.05.012
Muchane MN, Sileshi GW, Gripenberg S, Jonsson M, Pumariño L, Barrios E (2020) Agroforestry boosts soil health in the humid and sub-humid tropics: a metaanalysis. Agric Ecosyst Environ 295. https://doi.org/10.1016/j.agee.2020.106899
Nair PKR, Kumar BM, Nair VD (2009a) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23
Nair PKR, Vimla D, Nair B, Kumar BM, Haile SG (2009b) Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Policy 12:1099–1111
Nath AJ, Lal R, Sileshi GW, Das AK (2018) Managing India's small landholder farms for food security and achieving the "4 per Thousand" target. Sci Total Environ 634:1024–1033
Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Prod 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831
Newaj R, Dar SA, Yadav RS, Ajit, Sanker AK, Dhyani SK (2008) Management effect on growth, biomass carbon and nitrogen accumulation in *Albizia procera* at 4 years in agroforestry system. J Trop For 23:73–80
Newaj R, Chaturvedi OP, Handa AK (2016) Recent development in agroforestry research and its role in climate change adaptation and mitigation. Indian J Agrofor 18(1):1–9
Newaj R, Chaturvedi OP, Kumar D, Chavan SB, Rajawat BS, Yadav DK (2020) carbon sequestration potential in agroforestry systems for rehabilitating degraded lands of India. In:

Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 2. Springer, Singapore, pp 319–348

Niu X, Liu C, Jia X, Zhu J (2021) Changing soil organic carbon with land use and management practices in a thousand-year cultivation region. Agric Ecosys Environ 322. https://doi.org/10.1016/j.agee.2021.107639

Nkhuwa H, Kuntashula E, Kalinda T, Chishala B (2020) Effects of soil organic resource management practices on crop productivity and household income in Chipata district of Zambia. J Agric Ext Rural Dev 12(4):98–109

NRCAF (2007) Perspective plan vision 2025. National Research Centre for Agroforestry, Jhansi

Nyamadzawo G, Nyamugafata P, Wuta M, Nyamangara J, Chikowo R (2012) Rainfall, infiltrations and runoff losses under fallowing and conservation agriculture practices in contrasting soils of Central Zimbabwe. Water South 38:233–240

Okorio J, Maghembe JA (1994) The growth and yield of *Acacia albida* intercropped with maize (*Zea mays*) and beans (*Phaseolus vulgaris*) at Morogoro, Tanzania. For Ecol Manag 64:183–190

Ong CK, Odongo CW, Marshall FM, Black CR (1992) Water use of agroforestry systems in semiarid India. In: Calder IR, Hall RL, Adlard PG (eds) Growth and water use of forest plantations. Wiley, Chichester, pp 347–358

Ong CK, Black CR, Marshall FM, Corlett JE (1996) Principles of resources capture and utilisation of light and water. In: Ong CK, Huxley PA (eds) Tree–crop interactions—a physiological approach. CAB International, Wallingford, pp 73–158

Ong CK, Black CR, Wallace JS, Khan AAH, Lott JE, Jackson NA (2000) Productivity, microclimate and water use in *Grevillea robusta*-based agroforestry systems on hill slopes in Kenya. Agric Ecosyst Environ 80:121–141

Orr A, Kabombo B, Roth C, Harris D, Doyle C (2015) Adoption of integrated food-energy systems: Improved cookstoves and pigeonpea in southern Malawi. Exp Agric 51:191–209

Ortiz-Monasterio I, Wassmann R, Govaerts B, Hosen Y, Katayanagi N, Verhulst N (2010) Climate change andcrop production. In: Reynolds MP (ed) CABI climate change series. CAB International, Oxfordshire, pp 151–176

Padalia K, Bargali K, Bargali SS (2017) Present scenario of agriculture and its allied occupation in a typical hill village of Central Himalaya, India. Indian J Agric Sci 87(1):132–141

Pandey DN (2007) Multifunctional agroforestry systems in India. Curr Sci 92:455–463

Patra AK, Saxena J (2011) Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. J Sci Food Agric 91:24–37

Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P (2016) Climate-smart soils. Nature 532(4):9–57

Phiri E, Verplancke H, Kwesiga F, Mafongoya P (2003) Water balance and maize yield following improved *sesbania* fallow in eastern Zambia. Agrofor Syst 59:197–205

Quinion A, Chirwa PW, Akinnifesi FK, Ajayi OC (2010) Do agroforestry technologies improve the livelihoods of the resource poor farmers? evidence from Kasungu and Machinga districts of Malawi. Agrofor Syst 80:457–465

Rai AK, Solanki KR, Rai P (2002) Performance ofAnogeissus pendula genotypes under silviculture system. Indian J Agrofor 4:71–74

Rai P, Ajit, Chaturvedi OP, Singh R, Singh UP (2009) Biomass production in multipurpose tree species in natural grasslands under semiarid conditions. J Trop For 25:11–16

Rao Gururaja G, Nayak AK, Chinchmalatpure AR (2003) Salvadora persica: a life support species for salt affected black soils. Technical Bulletin 1/2003. CSSRI, Karnal, p 44

Reang D, Hazarika A, Sileshi GW, Pandey R, Das AK, Nath AJ (2021) Assessing tree diversity and carbon storage during land use transitioning from shifting cultivation to indigenous agroforestry systems: implications for REDD+ initiatives. J Environ Manag 298:113470. https://doi.org/10.1016/j.jenvman.2021.113470

Rees RM, Wuta M, Furley PA, Li C (2006) Nitrous oxide fluxes from savanna (miombo) woodlands in Zimbabwe. J Biogeogr 33:424–437

Rigal C, Xu J, Vaast P (2020) Young shade trees improve soil quality in intensively managed coffee systems recently converted to agroforestry in Yun nan Province, China. Plant Soil 453:119–137
Rizvi RH, Dhyani SK, Yadav RS, Singh R (2011) Biomass production and carbon stockof poplar agroforestry systems in Yamunanagar and Saharanpur districts of north-western India. Curr Sci 100:736–742
Roupsard O, Audebert A, Ndour A, Clermont-Dauphin C, Agbohessou Y, Sanou J, Koala J, Faye E, Sambakhe D, Jourdan C, le Maire G, Tall L, Sanogp D, Seghieri J, Cournac L, Leroux L (2020) How far does the tree affect the crop in agroforestry? New spatial analysis methods in a Faidherbia parkland. Agric Ecosyst Environ 296:106928. https://doi.org/10.1016/j.agee.2020.106928
Rowe EC, Hairiah K, Giller KE, Van Noordwijk M, Cadisch G (1998) Testing the safety-net role of hedgerow tree roots by 15 N placement at different soil depths. Agrofor Syst 43(1–3):81–93
Roy MM, Tewari JC, Ram M (2011) Agroforestry for climate change adaptations and livelihood improvement in Indian hot arid regions. Int J Agric Crop Sci 3(2):43–54
Roy S, Roy MM, Bano R, Saxena P (2017a) Soil microarthropods: biodiversity and role in grassland and agroforestry ecosystems. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 669–689
Roy S, Roy MM, Saxena P, Bano R (2017b) Role of entomology in sustaining agroforestryproductivity. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 691–704
Rusinamhodzi L, Corbeels M, Nyamangara J, Giller KE (2012) Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res 136:12–22
Sambane E (2005) Above ground biomass accumulation in fallow fields at the Nhambita Community, Mozambique. A dissertation presented for the degree of Master of Science, University of Edinburgh
Sapkota TB, Majumdar K, Jat ML, Kumar A, Bishnoi DK, McDonald AJ, Pampolino M (2014) Precision nutrient management in conservation agriculture-based wheat production of Northwest India: profitability, nutrient use efficiency and environmental footprint. Field Crop Res 155:233–244
Sapkota TB, Shankar V, Rai M, Jat ML, Stirling CM, Singh LK, Jat HS, Grewal MS (2017) Reducing global warming potential through sustainable intensification of basmati rice-wheat systems in India. Sustainability 9(6):1044
Sapkota TB, Vetter SH, Jat ML, Sirohi S, Shirsath PB, Singh R, Jat HS, Smith P, Hillier J, Stirling CM (2019) Cost-effective opportunities for climate change mitigation in Indian agriculture. Sci Total Environ 655:1342–1354
Sapkota TB, Singh LK, Yadav AK, Khatri-Chhetri A, Jat HS, Sharma PC, Jat ML, Stirling CM (2020) Identifying optimum rates of fertilizer nitrogen application to maximize economic return and minimize nitrous oxide emission from rice–wheat systems in the Indo-Gangetic Plains of India. Arch Agron Soil Sci 66(14):2039–2054
Sapkota TB, Jat ML, Rana DS, Khatri-Chhetri A, Jat HS, Bijarniya D, Sutaliya JM, Kumar M, Singh LK, Jat RK, Kalvaniya K (2021) Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions. Sci Rep 11(1):1–11
Setti AFF, Filho WL, Azeiteiro UM (2019) Ecosystem services and incentive mechanisms for environmental preservation in Brazil. In: Castro P, Azul A, Leal Filho W, Azeiteiro U (eds) Climate change-resilient agriculture and agroforestry. Climate change management. Springer, Cham. https://doi.org/10.1007/978-3-319-75004-0_3
SFR (2013) State of forest report. Forest Survey of India, Ministry of Environment, Forest & Climate Change, Dehradun, p 252
Sharma R, Xu J, Sharma G (2007) Traditional agroforestry in the Eastern Himalayan region: land management system supporting ecosystem services. Trop Ecol 48(2):189

Sharma G, Sharma R, Sharma E (2009) Traditional knowledge system in large cardamom farming: biophysical and management diversity in Indian mountainous regions. Indian J Tradit Knowl 8(1):17–22

Sheikh MA, Kumar M, Todaria NP (2015) Carbon sequestration potential of nitrogen-fixing tree stands. For Stud 62:39–47. ISSN 1406-9954. http://mi.emu.ee/forestry.studies

Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad Dev 29:3886–3897. https://doi.org/10.1002/ldr.3136

Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11:368. https://doi.org/10.3390/f11040368

Sida TS, Baudronb F, Kima H, Gillerc KE (2018) Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. Agric For Meteorol 248:339–347

Sileshi GW (2016) The magnitude and spatial extent of *Faidherbia albida* influence on soil properties and primary productivity in drylands. J Arid Environ 132:1–14

Sileshi G, Mafongoya PL (2003) Effect of rotational fallows on abundance of soil insects and weeds in maize crops in eastern Zambia. Appl Soil Ecol 23:211–222

Sileshi GW, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to planted fallow and green manure legumes in sub-Saharan Africa. Plant Soil 307:1–19

Sileshi GW, Akinnifesi FK, Ajayi OC, Muys B (2011) Integration of legume trees in maize-based cropping systems improves rainfall use efficiency and crop yield stability. Agric Water Manag 98:1364–1372

Sileshi GW, Debusho LK, Akinnifesi FK (2012) Can integration of legume trees increase yield stability in rain-fed maize cropping systems in southern Africa? Agron J 104:1392–1398

Sileshi GW, Mafongoya PL, Akinnifesi FK, Phiri E, Chirwa P, Beedy T, Makumba W, Nyamadzawo G, Njoloma J, Wuta M, Nyamugafata P, Jiri O (2014a) Fertilizer trees. In: Encyclopedia of agriculture and food systems, vol 1. Elsevier, San Diego, pp 222–234

Sileshi GW, Nyoka BI, Beedy TL, Chanyenga T (2014b) Modelling the scaling of stem growth with crown size and optimum stocking densities for systematic grid plantation of *Faidherbia albida*. New For 45:699–714

Sileshi GW, Nhamo N, Mafongoya PL, Tanimu J (2017) The stoichiometry of animal manure and its implications for nutrient cycling and agriculture in sub-Saharan Africa. Nutr Cycl Agroecosyst 107:91–105

Simelton E, Dam BV, Catacutan D (2015) Trees and agroforestry for coping with extreme weather events: experiences from northern and central Viet Nam. Agrofor Syst 89(6):1065–1082

Singh G (2009) Comparative productivity of *Prosopis cineraria* and *Tecomellaundulata* based agroforestry systems in degraded lands of Indian Desert. J Res 20(2):144–150

Singh G, Dagar JC (2005) Greening sodic lands: Bichhian model, Technical bulletin no.2/2005. Central Soil Salinity Research Institute, Karnal, p 51

Singh P, Gundimeda H (2014) Life cycle energy analysis (LCEA) of cooking fuel sources used in India households. Energy Environ Eng 2(1):20–30

Singh G, Singh NT, Tomar OS (1993) Agroforestry in salt-affected soils. Technical bulletin No.17, Central Soil Salinity Research Institute, Karnal, p 65

Singh YP, Sharma DK, Singh G, Nayak AK, Mishra VK, Singh R (2008) Alternate land use management for sodic soils. CSSRI Technical bull no. 2/2008. Central Soil Salinity Research Institute, Karnal, p 16

Singh AK, Arunachalam A, Ngachan SV, Mohapatra KP, Dagar JC (2014) From shifting cultivation to integrating farming: experience of agroforestry development in the northeastern Himalayan region. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services. Advances in agroforestry, vol 10. Springer, NewYork, pp 57–86

Singh M, Babanna SK, Kumar D, Dwivedi RP, Dev I, Kumar A, Tewari RK, Chaturvedi OP, Dagar JC (2021) Valuation of fuelwood from agroforestry systems: a methodological perspective. Agroforest Syst. https://doi.org/10.1007/s10457-020-00580-9

Sirrine D, Shennan C, Snapp S, Kanyama-Phiri G, Kamanga B, Sirrine JR (2010) Improving recommendations resulting from on-farm research: agroforestry, risk, profitability and vulnerability in southern Malawi. Int J Agric Sustain 8:290–304

Smith J (2010) Agroforestry: reconciling productivity with protection of the environment. A synopsis of research literature. Organic Research Centre, Elm Farm

Snapp SS, Blackie MJ, Gilbert RA, Bezner-Kerr R, Kanyama-Phiri GY (2010) Biodiversity can support a greener revolution in Africa. Proc Natl Acad Sci U S A 107:20840–20845

Snapp S, Kerr RB, Smith A, Ollenburger M, Mhango W, Shumba L, Gondwe T, Kanyama-Phiri G (2013) Modeling and participatory, farmer-led approaches to food security in a changing world: a case study from Malawi. Sécheresse 24:350–358

Soni ML, Beniwal RK, Yadava ND, Talwar HS (2008) Spatial distribution of soil organic carbon under agro forestry and traditional cropping system in hyper arid zone of Rajasthan. Ann Arid Zone:103–106

Soni ML, Yadava ND, Bhardwaj S (2013a) Decomposition and nitrogen release dynamics of fruit tree leaf litters in arid western Rajasthan. Ann Arid Zone 52(1):31–37

Soni ML, Yadava ND, Beniwal RK, Singh JP, Kumar S, Birbal (2013b) Grass based strip cropping systems for controlling soil erosion and enhancing system productivity under drought situations of hot arid western Rajasthan. Int J Agric Stat Sci 9(2):685–692

Soni ML, Subbulakshmi V, Yadava ND, Dagar JC (2017) Agroforestry for increasing farm productivity in water-stressed ecologies. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 369–411

Sridhar KR, Bagyaraj DJ (2017) Microbial biodiversity in agroforestry systems. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Singapore, pp 645–667

Ståhl L, Nyberg G, Högberg P, Buresh RJ (2002) Effects of planted tree fallows on soil nitrogen dynamics, aboveground and root biomass, N2-fixation and subsequent maize crop productivity in Kenya. Plant Soil 243:103–117

Swamy SL, Puri S (2005) Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry systems in India. Agrofor Syst 64:181–195

Swamy SL, Mishra A, Puri S (2003) Biomass production and root distribution of Gmelina arborea under an agrisilviculture system in subhumid tropics of Central India. New For 26:167–186

Takimoto A, Nair PKR, Nair VD (2008) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166

Tea Board of India (2014) Tea statistics. Ministry of Commerce & Industry, Government of India. http://teaboard.gov.in. Accessed 1 Dec 2021

Tewari JC, Moola-Ram RMM, Dagar JC (2014) Livelihood improvements and climate change adaptations through agroforestry in hot arid environments. In: Dagar JC, Singh AK, Arunachalam A (eds) Agroforestry systems in India: livelihood security & ecosystem services. Advances in agroforestry, vol 10. Springer, New York, pp 155–184

Thornton PK, Herrero M (2010) Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proc Natl Acad Sci U S A 107:19667–19672

Tschora H, Cherubini F (2020) Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. Glob Ecol Cons. https://doi.org/10.1016/j.gecco.2020.e00919

Valentini R, Arneth A, Bombelli A, Castaldi S, Cazzolla Gatti R, Chevallier F, Ciais P, Grieco E, Hartmann J, Henry M, Houghton RA, Jung M, Kutsch WL, Malhi Y, Mayorga E, Merbold L, Murray-Tortarolo G, Papale D, Peylin P, Poulter B, Raymond PA, Santini M, Sitch S, Vaglio Laurin G, van der Werf GR, Williams CA, Scholes RJ (2014) A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. Biogeosciences 11:381–407. https://doi.org/10.5194/bg-11-381-2014

Van Noordwijk M (ed) (2019) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor, p 420. http://www.worldagroforestry.org/trees-on-farms
Van Noordwijk M, Hoang MH, Neufeldt H, Oborn I, Yatich T (2011) How trees and people can co-adapt to climate change: reducing vulnerability through multifunctional agroforestry landscapes. Nairobi, World Agroforestry Centre (ICRAF)
Van Noordwijk M, Bizard V, Wangpakapattanawong P, Tata HL, Villamor GB, Leimona B (2014) Tree cover transitions and food security in Southeast Asia. Glob Food Secur 3:200–208
Van Zanten HHE, Mollenhorst H, Klootwijk CW, van Middelaar CE, de Boer IJM (2016) Global food supply: land use efficiency of livestock systems. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-015-0944-1
Verhulst N, Govaerts B, Sayre KD, Sonder K, Romero-Perezgrovas R, Mezzalama M, Dendooven L (2011) Conservation agriculture as a means to mitigate and adapt to climate change, a case study from Mexico. In: Wollenberg L (ed) Designing agricultural mitigation for smallholders in developing countries. Earthscan, London
Vermeulen S (2019) Realising ambitious targets and metrics for private-sector action on climate risks. In: Rosenstock TS, Nowak A, Girvetz E (eds) The climate-smart agriculture papers—investigating the business of a productive, resilient and low emission future. Springer
Weindl I, Lotze-Campen H, Popp A, Müller C, Havlík P, Herrero M, Schmitz C, Rolinski (2015) Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environ Res Lett 10:094021
Wise R, Cacho O (2005) A bioeconomic analysis of carbon sequestration in farm forestry: a simulation study of *Gliricidia sepium*. Agrofor Syst 64:237–250
World Bank (2004) Sustaining forests: a development strategy. The World Bank, Washington DC. ISBN 0-8213-5755-7
Yadava AK (2011) Potential of agroforestry systems in carbon sequestration for mitigating climate changes in Tarai region of Central Himalaya. Nat Sci 9(6):72–80
Zemmrich A, Manthey M, Zerbe S, Oyunchimeg D (2010) Driving environmental factors and the role of grazing in grassland communities: a comparative study along an altitudinal gradient in Western Mongolia. J Arid Environ 74(10):1271–1280
Zhang B, Zhao Y, Wang MZ (2008) Assessment of competition of water use between peanut (Arachis hypogaea) and Choerospondiasaxillaris in alley cropping systems in subtropical China. IAEA-TECDOC, pp 69–90
Zhaohua Z, Maiyi F, Sastri CB (1991) Agroforestry in China—an overview. In: Zhaohua Z, Mantang C, Shiji W, Youxu J (eds) Agroforestry in China. Chinese Academy of Forestry Republic of China and International Development Research Centre Canada, Singapore, pp 2–7
Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. Working Paper 179. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Bogor. https://doi.org/10.5716/WP14064.PDF
Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6:29987. https://doi.org/10.1038/srep29987

Chapter 19
Agroforestry as a Key Intervention to Achieve Nationally Determined Contribution (NDC) Targets

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Abstract Nationally determined contributions (NDCs) have emerged as the main tool for defining, communicating, and potentially reporting contributions of "parties" to the Paris Agreement on climate change. Agroforestry has been identified as a key part of most developing country NDCs; hence, it is a potentially important contributor to global climate objectives. This chapter explores the degree to which agroforestry is represented in current NDC ambitions, how its application is envisaged, and how its contribution could be enhanced. Agroforestry is one of the land uses with immense potential to fulfill commitments set out in NDCs and reduce emissions from agriculture; estimates of its potential to sequester vary widely, between 1.1 and 34.2 Pg C globally. Over 85% of the 22 NDCs assessed mentioned agroforestry as a strategy for achieving unconditional NDC commitments. By converting 25% of deforested areas to agroforestry, about 80% of the non-Annex I countries could achieve their unconditional commitments. The widespread use of agroforestry (about one billion hectares) and its familiarity among smallholder

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farmers and local practitioners makes it a potential low-hanging fruit for achieving NDC commitments, emission reduction in agriculture, and resilience. However, there are financial, policy, and technology challenges that should be addressed, including land and tree tenure and carbon rights in some countries, the potential impacts of climate change on the growing niches of tree species, and limited sources of quality germplasm.

Keywords Agroforestry · Climate change · NDCs · Paris Agreement · Policies · Potential

19.1 Introduction

Since the Paris Agreement of 2015, nationally determined contributions (NDCs) represent the main instrument for defining, communicating, and potentially reporting contributions of countries to long-term climate goals of the United Nations Framework Convention on Climate Change (UNFCCC). Unlike Kyoto Protocol, its predecessor, Paris Agreement employs a bottom-up approach requiring all global countries to contribute to emissions reductions through mechanisms such as agroforestry, among others (Muthee et al. 2022). The NDCs represent a process of prioritization in which countries consider options and possible scope for contributing to global climate mitigation objectives and, increasingly, adaptation objectives beyond 2020. NDCs cover most of the possible emission reduction pathways and sectors from energy, transport, and industry, through land use and land use changes, including agriculture and forestry, among others. Depending mainly on the sources of emissions and opportunities for emission reduction and resources, countries choose and prioritize different sectors. Most parties to the UNFCCC have already submitted NDCs, with UNFCCC(2021) reporting that 194 and 13 parties have submitted their first and second NDCs, respectively. Agricultural emissions in 2011 were estimated to be over five million tons of greenhouse gas (GHG), accounting for almost 13% of global emissions (Tubiello et al. 2014). Agricultural emissions are growing rapidly in developing countries and a large portion of this emission comes from the use of chemical fertilizers and unsustainable land use practices. Therefore, developing country NDCs tend to prioritize agriculture and forestry or, more generally, land use and land use change. Agroforestry has been identified as a key strategic dimension of many developing countries' NDCs, hence a potentially significant contributor to global climate change objectives.

Agroforestry, defined as the integration of trees into farms and their management in agricultural landscapes, can help in emission reduction and carbon neutrality in agriculture in several ways. Directly, agroforestry enhances carbon sequestration as trees grow and by substituting conventional fertilizer (a source of N_2O) through nitrogen fixation and soil fertility enhancement. Indirectly, agroforestry could help reduce emissions from adjacent forests as a sustainable intensification option (avoided deforestation) and by providing on-farm timber and tree products (avoided degradation) (Minang et al. 2014; Mbow et al. 2014a, b; Nath et al. 2021). Additionally, among the various perennialization options, agroforestry holds great potential for creating carbon sinks and mitigating GHG emissions from agriculture (Duguma et al. 2017), while also increasing adaptive capacity. Further, agroforestry has been used as a major pathway to enjoin forest communities to become partners in rehabilitating degraded forestlands.

This chapter explores the degree to which agroforestry is represented in current NDC ambitions, how its application is envisaged, and how its contribution could be enhanced. Twenty-two (22) developing country NDCs were reviewed. Key findings are presented in the ensuing sections, closing with policy recommendations for enhancing the potential of agroforestry to contribute to long-term climate change goals. The contributions of agroforestry to NDC targets beyond carbon are also discussed.

19.2 Methods

The study adopted the literature review approach, purposively sourcing relevant materials from different publications. The literature search included both grey and peer-reviewed literature on "agroforestry" and "national determined contributions" with a focus on "non-Annex 1 countries" as classified under the UNFCCC. Data was extracted from different sources for deeper analysis using an equation to compute agroforestry carbon stock and identify different pathways through which agroforestry contributes to other sectors beyond the set carbon targets in different NDCs.

The analysis focused on developing countries, classified in the UNFCCC as non-Annex I countries. Twenty-two (22) non-Annex I countries that submitted their commitments in the form of NDCs were selected based on how clearly the NDCs presented the emission targets, the business as usual (BAU) projected emission amount at target year, and the commitments to emission reduction based on the BAU emission scenario. The following countries were used in this analysis:

1. Brazil, Argentina, Peru, Costa Rica, and Jamaica in the Caribbean, Central and South America,
2. Tunisia, Ghana, Togo, Burkina Faso, Niger, Chad, Central African Republic (CAR), Ethiopia, Djibouti, Kenya, Uganda, Malawi, Zambia, Botswana and Namibia in Africa, and.
3. Indonesia and Vietnam in Asia.

The NDCs were downloaded from the UNFCCC site where the commitments are hosted (NDC Registry, n.d.). It is important to note that this analysis does not take into account progress made since submission. Data on the extent of deforestation was obtained from FAO (2015) specifically from the Global Forest Resources Assessment 2015.

The computation of agroforestry's contribution to NDCs was done by adopting the following assumptions. First, most agroforestry land uses are traditional practices familiar to local actors and were often mentioned in the unconditional commitment as practices where no external support is critically needed. Second, unconditional commitments were considered more realistic and achievable and less dependent on often unpredictable external resources. Hence, our analysis focused on unconditional commitments only.

Equation (19.1) was used to compute the NDC contribution of agroforestry.

$$\text{Agroforestry carbon stock} = \text{Carbon density} \ast \text{Conversion rate} \ast \text{Deforested area}\,(2000 - 2015) \tag{19.1}$$

* NDCs commitment period.

Note: Annual carbon increments of agroforestry = 3.3 Mg ha^{-1} yr^{-1} (Palm et al. 2000).

Conversion rate = 25%, 50%, or 100% of the deforested area NDCs commitment period = Target year—base year.

19.3 Agroforestry for Achieving Emission Reduction Targets

Despite varying estimates of the area under agroforestry, there seems to be consensus among the different sources that there is close to a billion hectare (ha) of land covered by agroforestry practices (Table 19.1). The estimate of carbon stock from this practice is in the range of 1.1–3.3 Pg C. Zomer et al. (2016) however, put the estimate higher. The authors estimated biomass carbon of 45.3 Pg C on agricultural land in 2010, of which approximately 34.2 Pg C (75%) was contributed by tree components in the agricultural systems. Table 19.1 summarizes the different estimates of carbon sequestration potential in agroforestry. A recent follow-up study (Zomer et al. 2022) estimated global increases in carbon stock of 4−6 PgC for "incremental change" (increasing tree cover by no more than 10% in agricultural areas that are currently below median tree cover) and even 12−19 PgC for "systemic change" (where tree cover in agricultural lands increases to the 70th percentile for the ecological zone).

Table 19.1 Area estimates of agroforestry and its carbon sequestration potential

Source	Estimated area of agroforestry	Estimated carbon stock
Zomer et al. (2016)[a]; Zomer et al. (2014)[a]; Nair et al. (2010)	Over one billion ha	3.3 Pg C[b]
IPCC (Watson et al. 2000)	400 million ha	2.78 Pg C
	630 million ha (potentially suitable area)	0.012 Pg C[c]
Albrecht and Kandji (2003)	585–1215 million ha	1.1–2.2 Pg C

[a]These sources refer to agroforestry as agricultural lands with at least 10% tree cover
[b]We used 3.3 Mg ha^{-1} yr^{-1} average carbon stock value for agroforestry (Palm et al. 2000)
[c]The value is estimated assuming a third of the 630 Mha could be converted to agroforestry especially in developing countries. Pg C = 10^{15} g C; 1 g C = 3.67 g CO_2eq

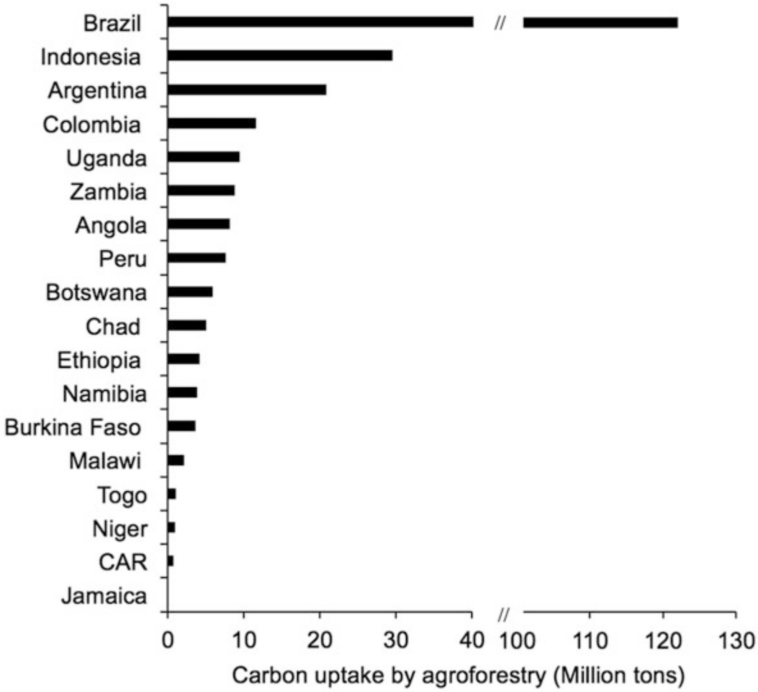

Fig. 19.1 Potential amount of carbon sequestered by agroforestry if implemented as an improvement in cropland systems in 80% of the deforested area during the NDC commitment period

Gibbs et al. (2010) found that more than 80% of the new croplands created in the tropics between 1980 and 2000 came at the expense of clearing intact and disturbed forests. West et al. (2010) estimated that with every ton of crop yield produced annually per ha in the tropics, close to 77 Mg C ha^{-1} is lost. With an average crop yield of 1.7 Mg ha^{-1}, the associated carbon loss is 120.3 Mg C ha^{-1}. Hence, it is imperative to find means of reducing the emissions or creating offsetting mechanisms to reduce the system level GHG emissions. Agroforestry plays a crucial role in achieving this (Oino and Mugure 2013). Smith et al. (2008) listed agroforestry as one of the key strategies to mitigate emissions from agriculture. Trees in the form of agroforestry practices could offset such emissions from within the landscape from which they occur.

Combining results from Sanchez (2000) of 57 Mg C ha^{-1}sequestration from agroforestry when it is established in deforested areas and the 120.3 Mg C ha^{-1} loss described in West et al. (2010), it is estimated that agroforestry cuts emission from agriculture by almost half (47%). On the other hand, Watson et al. (2000) estimated that by improving tree management on croplands, it is possible to gain 0.08–0.33 Mg C ha^{-1} yr^{-1} with an average value of 0.22 Mg C ha^{-1} yr^{-1} for non-Annex I countries considering the policy and institutional challenges. Figure 19.1 presents the results of the emission reduction potential using a scenario where improved tree management is practiced on croplands.

19.4 Agroforestry's Contribution to Achieving NDC Targets

In many non-Annex I countries, NDCs have both adaptation and mitigation components. An in-depth look at the NDCs of selected countries revealed that agroforestry is included among key strategies toward achieving the unconditional targets of NDCs. Except for two countries, the remaining 20 prioritized agroforestry as an intervention in their NDC. The dominance of agroforestry in NDCs is particularly high in sub-Saharan Africa (Fig. 19.2). Note that this may not necessarily mean that they implement more agroforestry practices compared to other countries.

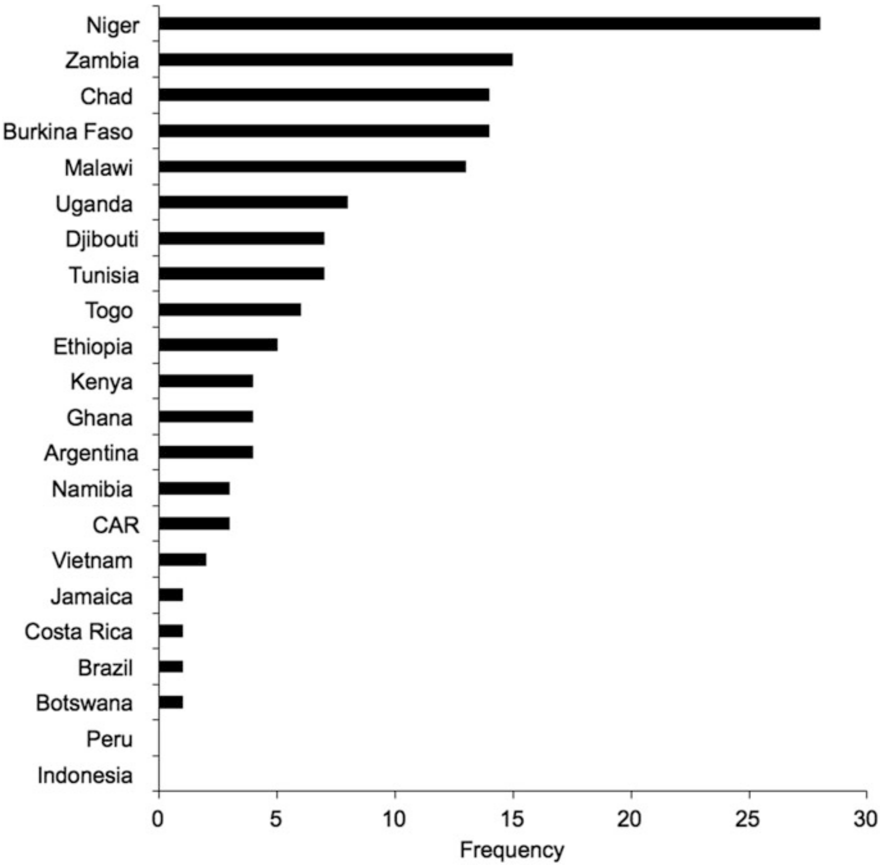

Fig. 19.2 Frequency of the word "agroforestry" and its synonyms in NDCs of selected countries

Table 19.2 Agroforestry's potential to achieve NDC targets under different scenarios

Country	Emissions to be reduced at target year (Gt CO_2 eq)	Forest cover loss 2000–2015 (1000 ha)	Sequestration potential (Gt CO_2 eq) achievable through agroforestry establishment		
			Scenario 1: Using 25% of the 2000–2015 deforested areas	Scenario 2: Using 50% of the 2000–2015 deforested areas	Scenario 3: Using 100% of the 2000–2015 deforested areas
Argentina	0.1090	4748	0.359	0.719	1.438
Brazil	0.9030	27,736	2.099	4.199	8.398
Burkina Faso	0.0078	898	0.063	0.125	0.250
Central African Republic	0.0055	234	0.014	0.028	0.057
Chad	0.0417	1451	0.088	0.176	0.351
Ethiopia	0.2550	1206	0.073[a]	0.146[a]	0.292
Indonesia	0.8340	8399	0.509[a]	1.017	2.034
Jamaica	0.0011	6	0.000[a]	0.001[a]	0.002
Malawi	0.0048	420	0.038	0.076	0.153
Namibia	0.0020	1113	0.067	0.135	0.270
Niger	0.0034	186	0.017	0.034	0.068
Peru	0.0597	2174	0.132	0.263	0.527
Togo	0.0043	298	0.018	0.036	0.072
Uganda	0.0170	1792	0.163	0.326	0.651
Zambia	0.0200	2499	0.151	0.303	0.605

[a]Denotes cases where conversion of deforested areas may not be sufficient to meet the NDCs commitment

Table 19.2 presents the contribution of agroforestry to NDC targets under different conversion scenarios of deforested areas. More than 80% (12 out of 15) of the countries that experienced deforestation between 2000 and 2015 could meet their unconditional NDC targets by converting 25% of the deforested lands to agroforestry. Such action enables countries to meet global, national, and local policy objectives such as their Bonn Challenge commitments, REDD+ objectives and SDG targets

Trees sequester carbon in their biomass. Plant biomass is built through the process of photosynthesis, where plants absorb carbon dioxide, one of the major greenhouse gases (Dhyani et al. 2020). By being carbon sinks, plants have become one of the greatest blessings to our planet. In fact, all other means of absorbing carbon dioxide out of the earth's atmosphere come at an extra cost. But trees do it for free: absorbing carbon is their basic mandate (Table 19.3).

Trees enrich the soil by their litter contribution and periodic shedding and decomposition of their roots. This increases the soil organic matter content, which

Table 19.3 Agroforestry potential to sequester carbon

Description (source)	C sequestration ($Mg\ C\ ha^{-1}\ yr^{-1}$) [range]	C stock ($Mg\ C\ ha^{-1}$) [range]	Rotation period (yr)
Parklands AFS *Faidherbia albida* dominated[a]	0.5 [0.2–0.8]	33.4 [5.7–70.8]	50
Home gardens[a]	0.6 [0.4–0.8] 2.24 [0.22–5.8]	19.0 15.7	25 25
Rotational woodlots Tree planting—windrows[a]	3.9 [2.2–5.8]	18.5 [11.6–25.5]	5
Long term fallows, regrowth of woodlands in abandoned farms[a]	3.12 [1.0–6.7]	77.9 [12–228]	50
AFS and integrated land use[a] Soil C in agroforestry systems	0.9 [02.5–1.6]	90.7 [13–300]	nd
Agrisilvicultural[b]	1.13	42.6 [28.9–56.4]	nd
Agrosilvopastoral[b]	2.77	73.4 [34.9–111.9]	nd
Silvopastoral[b]	2.65	42.7 [11.2–74.1]	nd

nd stands for no data
[a]Mbow et al. 2014a
[b]Nath et al. 2021)

is composed of organic carbon to a large extent. The fact that tree roots keep soil erosion to the minimum through their stabilization effects is among the major impact pathways to avoid emissions from the soil and loss of soil carbon stock, as Aponte et al. (2012) establish.

19.5 Pathways for Agroforestry to Contribute to NDC Targets Beyond Carbon

Besides the enormous emission reduction potentials described above, agroforestry practices are directly linked to the livelihood of 12–16% of the global population. Leakey and Sanchez (1997) estimated that close to 1.2 billion people (16% of the current global population) directly depend on the products and services of agroforestry. Zomer et al. (2014) estimated that the area under agroforestry systems in the years 2008–2010 is directly linked to the livelihoods of about 900 million people (12% of the global population). Very few interventions support such proportions of the global population while also mitigating emissions emanating from human activities (Van Noordwijk 2019).

Implementation of agroforestry can help systems adapt to greater climate variability by increasing structural and temporal diversity of the production system and, therefore, increasing capacity for supporting various ecological and production services that impart resilience in the face of climate change impacts (Verchot et al. 2007). By altering the microclimate, agroforestry practices can promote resilience to shifting temperature, precipitation variation, and strong winds associated with storms, therefore producing more favorable conditions for crops, forage, and livestock production (Schoeneberger 2009). For instance, in coffee agroforestry systems, it was proven that crops grown under heavy shade (60–80%) were kept 2–3 °C cooler during the hottest times of the day than crops under light shading (10–30%) (Lin 2007) and lost 41% less water through soil evaporation and 32% less water through plant transpiration (Lin 2010).

Agroforestry also provides greater habitat diversity to support organisms (e.g., native pollinators, beneficial insects) (Schoeneberger et al. 2012) and provide naturally occurring cobenefits such as enhanced nutrient cycling, integrated pest management, and increased resistance to diseases, which additionally protect farm production (Jose 2009). It further offers greater economic stability and reduced risk to smallholder farmers vulnerable to the effects of climate change by improving production and creating more diversified enterprises with greater income distribution over time (e.g., short-term (forage and/or livestock) versus long-term (timber) income sources in a silvopastoral system). Kristjanson et al. (2012), in a study that involved about 700 households in East Africa, found that at least 50% of those households had begun planting trees on their farms to adapt to the impacts of climate change.

The following sections describe various pathways through which AF can contribute to the beyond carbon NDC targets.

19.5.1 Agroforestry to Reduce Deforestation and Forest Degradation

Impact pathway 1: When more trees are grown in the land outside forests, there will be a supply of wood products such as timber and firewood thus, reducing the need to cut down trees from the forest, hence reducing forest degradation (Minang et al. 2014).

Impact pathway 2: Among the key reasons why people cut down trees or clear forest plots is because they need to earn money by selling the timber or need to create farmlands that can produce food (Jamnadass et al. 2013). Often forest plots are cleared because of the thinking that the forest soils are fertile, and can produce more food within the first few years. Among the key drivers of such clearance is the degradation of farmlands. Moreover, there is need to produce more food to supply food to the growing population. If nitrogen-fixing trees are integrated into the farming systems, however, farmlands become more productive on a sustainable basis as the trees fix nitrogen and the roots keep the soil erosion to a very low level (FAO 2017). This in turn boosts food production. Trees can also be sold to earn income and hence reduce the need to clear forest plots to generate income by producing marketable timber.

19.5.2 Agroforestry for Nutrition and Food Security

Impact pathway 3: Fruit tree agroforestry is among the most direct contributors to the food and nutrition security of households (Akinnifesi et al. 2008). The fruits, nuts and other edible parts that are produced feed families. Second, the fruits can be sold to generate income that can be used to purchase food that the family or households require daily, in addition to supporting their livelihood needs (Akinnifesi et al. 2008; Muthee et al. 2021). The agroforestry systems of traditional communities exhibit considerable variation in crop diversity, influenced by crop composition and rotation, and hold promising potential to address food, nutrition and livelihood issues, and socio-economic and environmental sustainability.

Impact pathway 4: Trees contribute extensively to farm productivity (Kuyah et al. 2021). Leguminous trees, often referred to as fertilizer trees, contribute significantly to soil fertility and hence land productivity, thereby improving household food supply (Garrity et al. 2010; Sileshi et al. 2014).

Impact pathway 5: Fodder trees are the main sources of feed and nutrients for livestock in much of the global south, particularly during dry seasons, ensuring milk and meat production (Place et al. 2009; Franzel et al. 2014). In drier agroecosystems, livestock makes up the largest share of the livelihood and food security component (Chakeredza et al. 2007).

Impact pathway 6: Trees raise animal productivity by improving microclimates. Goats, sheep and other livestock benefit from shade, especially during hot dry months. Ellison et al. (2017) indicated that areas occupied by trees are cooler and moister.

Impact pathway 7: Agroforestry reduces the invasiveness of pests and diseases in croplands (Lasco et al. 2014; Pumariño et al. 2015; Sileshi et al. 2008). Harrison et al. (2019) found that combining multipurpose trees and companion plants with crops reduces invasion of pests such as Fall Army Worm (*Spodoptera frugiperda*).

19.5.3 Agroforestry for Disaster Risk Management

Impact pathway 8: Through their root structure, trees keep soil layers together and lessen the probability of landslides and erosion damaging slopes (Ammann et al. 2009).

Impact pathway 9: Tree canopies reduce soil erosion by regulating throughfall and the splashing effects of raindrops, as argued by Ma et al. (2014). When rain falls onto the soil's surface with decreased energy, the likelihood of surface flow that might lead to flooding is lessened. This is largely because the time lapse, depending on the soil condition, creates a chance for more water to percolate into the soil allowing a greater volume of water to infiltrate. On a larger spatial scale, such roles could play a vital role in reducing flooding. Tree roots influence soil porosity (particularly the microporosity) and enhance infiltration and water percolation into the soil rather than flowing on the surface (van Noordwijk et al. 2019).

Impact pathway 10: Tree stems serve as barriers to rock fall, especially on steeply sloping areas (Liu and Li 2020). Upland area forests and rows of trees therefore play a significant role in disaster risk reduction.

Impact pathway 11: In many countries, drought is a recurrent disaster. Through the process of evapotranspiration, trees and forests contribute water vapor to the atmosphere as explained by Wheeling (2019). This enhances cloud formation, which could increase the chances of rain in the country or region depending on wind conditions.

Impact pathway 12: Trees, particularly those in riverine ecosystems, reduce coastal erosion and thus risk of flooding. They reduce the risks associated with storm surges and even tsunamis (van Noordwijk et al. 2019).

Impact pathway 13: Trees are an integral component of larger socioecological systems that enhance resilience to various risks and hazards.

Impact pathway 14: Trees are key to restoring areas damaged by natural hazards such as landslide, tsunamis and storm surges.

Impact pathway 15: Agroforestry systems (AFS) may be considered nature-based solutions capable of addressing the twin crises of climate change and biodiversity loss. AFS may be treated as nature-based solutions (Seddon et al. 2020) as they contribute to the restoration of depleted land. In addition, they address subsistence farmers' social and livelihood challenges by providing resources for consumption (i.e., resource saving) as well as selling (i.e., earnings) (Reang et al. 2021).

19.5.4 Agroforestry for Sustainable Water Supply

Impact pathway 16: Trees influence soil macro and microporosity through the configuration of their root structures, resulting in more water infiltration into the soil (Xie et al. 2020). After passing through the various soil layers, this water reaches the below ground aquifers that serve as the main source of freshwater for human consumption all around the globe. If trees are absent or insufficient, the rate at which aquifers get enriched could be very slow, resulting in a shortage of freshwater for human and animal consumption (Ilstedt et al. 2016).

Groundwater recharge usually increases at medium tree cover level, particularly in drier ecosystems such as the Sahel (Ellison et al. 2017). In West African woodland, intermediate tree cover of 5–10 trees hectare appears optimal for groundwater recharge (Ilstedt et al. 2016), With numerous people relying on boreholes for water in many African countries, especially the Sahel, groundwater recharge is critical to cope with long dry seasons.

Impact pathway 17: Trees also play a vital role in the supply of clean water, particularly by filtering and reducing sediment entering waterways, as Abatneh et al. (2014) note. For this reason, streams in forested ecosystems have lower sediment loads and less turbidity than streams in degraded landscapes.

Impact pathway 18: Trees in watersheds play a critical role in reducing siltation of dams and water collection points which, if not for the trees, may finally be filled with silt and have less and less volume for water storage.

Impact pathway 19: Shade trees established around water collection points reduce evaporative loss due to heat (high temperature) in dry agroecosystems (Lasco et al. 2014). This minimizes water loss and hence prolongs the water supply for households and domestic animals.

19.5.5 Agroforestry for Biodiversity Conservation

Impact pathway 20: Trees provide habitat for animals. Agroforestry trees provide the most critical habitats for wild animals in farming systems. Birds, small mammals, reptiles, and insects reside in trees on farms. AFS also act as in-situ conservation sites for many native endangered plant and animal species. Trees on farms and other agroforestry systems provide feed and nesting sites for the broader animals that often come to the farms e.g., birds, small mammals, reptiles, and insects (Franzel et al. 2014).

Impact pathway 21: Conserving tree genetic resources is the key element of biodiversity conservation. Trees on farms and other agroforestry systems act as refugia for so many wild animals in the landscapes. The most notable ones in tropical areas are birds, primates, reptiles etc.

Impact pathway 22: Most agroforestry systems harbor a greater diversity of animals and plants than adjacent plantations or agricultural fields. In Costa Rica, cocoa agroforestry systems were found to conserve species-rich but modified assemblages of tropical birds and bats (Harvey and Villalobos 2007). Central American coffee and cocoa agroforestry systems held almost as many species of birds as intact forest and several times more than monoculture banana or maize.

19.5.6 Agroforestry for Energy Supply

Impact pathway 23: Wood from trees has always been one of the cheapest energy sources in tropical and subtropical areas. Humans have relied on firewood for millennia. Agroforestry practices provide one of the most accessible wood sources while also benefiting communities to have additional benefits as (Liyama et al. 2014) note. The supply of firewood from trees is, in fact, the most direct contribution of trees to the energy agenda highlighted in the NDCs. There is a growing trend now of farmers gaining substantial volumes of firewood from on farm tree pollarding and pruning (Njenga et al. 2017). The authors argue that agroforestry provides households with a cheap and convenient source of firewood.

Impact pathway 24: Trees are also the major ingredient of charcoal, the second most popular energy source after firewood in the developing world.

Impact pathway 25: Watershed-level roles played by trees contribute significantly to water availability for hydroelectric dams which are vital sources of electricity in many countries (e.g., Malawi, Zambia, Uganda).

Impact pathway 26: Trees have become critical biofuel sources, e.g., oil from oil palm and *Jatropha* and *Croton* species are among the important tree-derived biofuels currently (Dobie and Sharma 2014).

Impact pathway 27: Woodlots are one of the most common on-farm trees growing designs to supply wood for energy in the Global South. National and subnational governments have also taken up large-scale woodlots to produce wood that could be predominantly used for firewood. Even considering the domestic supply in rural areas alone, on-farm wood contribution to the global supply chain cannot be displaced. Of the 3.9 billion m^3 global roundwood production in 2019, a total of 1.9 billion m^3 was in the form of fuelwood. This is about 48% of the total wood production (FAOSTAT 2021).

19.5.7 Agroforestry for Adaptation to Climate Change

Agroforestry plays a crucial role in adapting to climate change effects. USDA (2015)) lays out several adaptation benefits of Agroforestry (Table 19.4).

Table 19.4 Adaptation benefits of agroforestry practices (based on USAID 2015)

Risk	Adaptation	Agroforestry practice
Intense precipitation events	Slow water runoff to reduce flooding, soil erosion, and water pollution	Riparian forests buffers, alley cropping
Increased temperature	Reduce heat stress on animals by providing shade	Silvopasture
Increased frequency and intensity of drought	Reduced evapotranspiration by reducing windspeed	Windbreaks
Increased storm intensity (wind and precipitation)	Protect crops by creating microclimates	Windbreaks, alley cropping
Changes in growing seasons due to temperature and precipitation	Protect crops by creating microclimates	Windbreaks, alley cropping, forest farming
Winter storm and cold temperature extreme	Reduce cold stress on animals by providing shelter	Silvopasture, windbreakers
Increased insect and disease problems	Control pests by providing habitat for beneficial insects	Windbreaks, riparian forest buffers, alley cropping
Increased possibility of crop failure due to other risks	Reduce total crop loss by increasing crop diversity	All agroforestry practices

19.6 Case Studies

19.6.1 India

Although agriculture is the major land use occupying 55% of India's total land area (Nath et al. 2018), it is not prominently featured in India's NDC. Nath et al. (2021) analyzed the C sequestration potential of various agroforestry systems and its relevance to India's NDC. Assuming no significant change in area under agroforestry, the total C sequestered by 2050 was projected to be 4.2, 4.5 and 1.5 Pg CO_2 eq in agrisilvicultural, agrosilvopastoral, and silvopastoral systems, respectively. With an increase in 5% of the current area at 5-years intervals, the total CO_2 eq sequestered by 2050 was estimated at 5.4 Pg in agrisilvicultural, 5.8 Pg in agrosilvopastoral and 1.9 Pg in silvopastoral systems. The analysis also found that expansion of the area under agroforestry by a mere 30% has the potential to offset significant proportions of India's total emissions by 2050.

19.6.2 Vietnam

A recent analysis by Mulia et al. (2020) indicated that agroforestry can greatly contribute to Vietnam's 2021–2030 NDC to offset the GHG emissions of the agriculture sector. Existing agroforestry systems in Vietnam cover over 0.83 million hectares storing on average 1346 million Mg CO_2 eq in aboveground, belowground and soil carbon. Mulia et al. (2020) estimated that these systems could be expanded to an area of 0.93–2.4 million hectares, 10% of which considered highly suitable for production, with a carbon sequestration potential of 2.3–44 million Mg CO_2 equivalent over the period 2021–2030.

19.6.3 Brazil

The sheer scale of the Brazilian NDC goals 12 Mha by 2030 compared with the approximately 0.3 Mha of vegetation currently restored across the country (IUCN 2016). Currently, the Brazilian silviculture sector has an annual planting capacity of approximately 0.7 Mha, suggesting the need to adopt a gradual restoration schedule with an annual growth rate of 22% per year to achieve full recovery by 2030 (Instituto Escolhas 2016). The Forest Cacao Project in Brazil has the potential to become an important benchmark to show how it is possible to expand the cocoa commodity supply chain sustainably while promoting the restoration of native forests and advancing the country's NDC commitment. The total area to be restored and suitable for cacao agroforestry systems in Pará State is 557,500 ha contributing to Brazil's NDC (IUCN 2016).

19.6.4 Lao PDR

Lao PDR NDC aims to establish agroforestry system in 30,000 ha of nonforested land to offset GHG emission. One of the studies with rubber-based agroforestry covering an area of 970 ha, in Bolikhamsai province in Central Lao PDR has shown to sequester approximately 1.1 million Mg CO_2e by 2037 (36,916 Mg CO_2e year^{-1}) (FCPF 2018). However, the estimated CO_2 eq values from proposed 30,000 ha are not available in the Lao's literature or elsewhere.

19.7 Enablers for Effective Implementation of Agroforestry to Contribute for Achieving NDC Targets

In order to identify and understand the enablers, it is crucial to understand the barriers that prevent people from adopting and expanding the practice of agroforestry. Often this comes down to barriers to tree growing. Van Noordwijk et al. (2008) listed several of these (Box 19.1).

Box 19.1: Key Barriers to Growing Trees (van Noordwijk et al. 2008)
Numerous factors affect tree growing by farmers.

1. **Land tenure and land use restrictions** are the most common barriers to the growing of trees.
2. **Tree tenure** is one of the most important determinants of whether farmers decide to grow trees.
3. **Access to high-quality planting material** remains a challenge, especially at the farmer level.
4. Lack of management **skill and information** often constrain production for lucrative markets.
5. Overregulation often restricts **market access** for farmer grown tree products, partly due to rules intended to curb illegal logging from natural forests or government plantations.
6. There is a lack of **reward mechanisms** for environmental services provided by agroforestry.
7. There is a lack of **supportive legal and institutional frameworks** for smallholder tree growing and agroforestry in general.
8. In drier agroecosystems, **water** is among the key determinants of tree growing.
9. **Site-species suitability knowledge** is limited especially with climate change altering the suitability of specific sites for trees.

The following sections give in-depth insights into the barriers and how an enabling context could be framed for effective tree growing.

Planting Materials Farmers often lack information on the choice of species, access to planting materials, including seed, nursery management, and capacity in vegetative propagation and marketing, especially of indigenous tree seedlings and related products. Access to quality inputs for both agriculture and forestry is a challenge with few national institutions mandated to support these to any extent. These challenges can be solved through:

- Supporting knowledge on tree establishment, management and harvesting in farmlands.
- Providing guidelines and techniques on quality germplasm collection, storage and use.
- Improving tree establishment practices to help restore agricultural and remaining and formerly forested areas.
- Providing knowledge on species diversity, conservation, and issues of invasive species, including how to remove and prevent their introduction and spread.

Livestock Management The most important goal of grazing management is to prevent large numbers of animals from congregating in any one location for too long. Thus, distribution is a major concern for livestock and land managers. Successful livestock management can be achieved through:

- Increasing the number of watering points on pastureland to avoid livestock congestion on one water point.
- Provision of supplements such as salts, minerals and feeds can be used to entice livestock away from overgrazed lands and onto underutilized ones.
- Using an appropriate stocking rate to balance the forage demand rate by grazing animals with the forage production rate.

Integrated Pest and Disease Management (IPM) This is a collection of pests management strategies that incorporates a range of pests control tactics. The goal is to prevent pests from reaching economically or aesthetically damaging levels with the least environmental risks. It involves anticipating pest outbreaks and the prevention of potential damage. To be successful, IPM programs must be based on identifying pests, accurate measurement of pest populations, assessment of damage levels, and knowledge of available pest management strategies. Advocating only-when-needed judicious use of chemical pesticides, IPM is part of a suite of nature-based and climate-smart solutions for smallholders that also reduces input costs (Egan and Chikoye 2021).

The following steps should be taken before implementing an IPM program:

- Identify the pest.
- Set up a monitoring program.
- Know the pest level that triggers control.

- Know what control methods are available.
- Evaluate the benefits and risks of each method.

Technical Capacity Skilled manpower is essential especially in cases where there are development activities such as those that are needed to achieve the NDC targets. It enables proper utilization of available means and resources in effective ways to fulfill the needs of the country. Trainings and workshops can be carried out to improve the effectiveness of existing skilled human resources.

Tree Product Markets In most countries, nature-based enterprises generate substantial benefits financially though some might have considerable ecological consequences. Nature-based enterprises include firewood collection, timber harvesting, ecotourism, and food processing. This sector faces many challenges, solutions to which can include:

- Improving access to market through increased investment in rural marketing infrastructure.
- Supporting labor saving devices and technologies to increase productivity.
- Promoting financial services and improving the skills and knowledge of value chain actors.

Water Infrastructure As much as it is paramount to have a reliable source, climate change has made water a very scarce resource. Water is a crucial component in the success of NDCs. Its availability can be improved through the following ways:

- Appropriate assessment of groundwater level to yield knowledge necessary for informed management and governance.
- Supporting the installation of boreholes for water supplies in strategic water points.
- Introduction of water harvesting options to reduce loss of rainwater.
- Where boreholes are considered, optimal access should be developed while ensuring no over-exploitation takes place.

Land and Tree Tenure Land tenure is an institution that regulates behavior. Rules of land tenure define how property rights to land are to be allocated within societies. Land tenure systems determine who can use what resources for how long, and under what conditions.

Tree tenure consists of a bundle of rights over trees and their produce, which different people may hold at different times. These rights include the right to own or inherit trees, the right to plant trees, the right to use trees and tree products, the right to dispose of trees, and the right to exclude others from the use of trees and tree products. Securing land rights particularly of women can accelerate realization of NDCs targets and slow down climate change (Siegele 2020).

Countries that invested in the technical and institutional infrastructure required for efficient and equitable land tenure administration have developed much faster with a far higher level of food security, health and welfare. Land tenure is important, especially in rural development interventions that emphasize building people's endowments of assets so they can enjoy sustainable livelihoods. A livelihood is sustainable when it can cope with, and recover from stresses and shocks, and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.

Sustained Commitment Most tree planting in the past has failed because emphasis was largely on planting the trees rather than caring for them to grow. Most planting activities are judged to be successful by the number of tree seedlings put in the soil rather than by the number of trees grown. There is a strong need for sustained commitment and long-term partnership to achieve successful implementation and impactful agroforestry practices.

19.8 Recommendations for Realizing Agroforestry Contributions in NDCs

Despite the tremendous potential of agroforestry described, quantified, and qualified above, challenges remain. We present options for mitigating these challenges as espoused in the literature.

(a) *Increased investments in tree germplasm supply systems and knowledge systems for agroforestry are crucial*: Smallholders experience difficulties in accessing—at the right time, in the right quantities and of high quality—the trees that they want to plant. Therefore, increased investments in planting material infrastructure are necessary to meet demand for planting materials now and in the future. Training on seedling and germplasm management as well as supply of the planting materials is key to promote adoption of agroforestry. Knowing the right tree for the right place and for the right purpose as well as recognizing good quality planting material represent a set of examples of the knowledge demands of agroforestry. World Agroforestry (ICRAF) has tools that can help determine the right trees for the right place in terms of agroecology (www.vegetationmap4africa.org).

(b) *Innovative blended financing mechanisms—including blending mitigation and adaptation finance, and impact investment—could facilitate rapid transformation through the effective implementation of agroforestry practices*: Agroforestry takes on average 3–5 years before producing and delivering benefits. Therefore, farmers need financing and technical support during the early phases. Blended finance or a coinvestment approach is needed in order to achieve results at scale. This involves looking at multiple sources (government, multi- and bilateral donors, private sector, philanthropic capital, communities, etc.), multiple streams (both mitigation and adaptation), and different finance instruments (e.g., grants, government investment, philanthropic capital, money from Corporate Social Responsibility and other emerging innovations for financing green initiatives (e.g., Green Bonds)). Innovative blended financing also comes with the growing need for a robust accounting and accountability system with reliable data and good transparency.

(c) *Devising policy instruments that clarify land and tree tenure and carbon rights is fundamental to motivate local actors to implement agroforestry within their routine agricultural activities, which then contributes to achievements of the NDCs*: There is evidence that nonfinancial incentives emerge as a feasible and preferred stimuli of change in landscapes with sustainable benefits, and that when local actors are recognized as resource rights owners, they are more incentivized to sustainably manage forest areas. For instance, in Viet Nam in Bac Kan Province, the establishment of long-term Land Use Right Certificates (LURC) and community forest management on previously "unmanaged" forest was a key incentive for people to successfully adopt agroforestry on sloping land, replace maize mono-cropping, and restore encroached forests (Crossman et al. 2016). In Tanjabar Province, Indonesia, the development of a community forestry license providing conditional land rights to the communities that managed and cultivated in peatland areas had significant impact as local actors took it as a solution to address land conflicts and mitigate further land degradation in the peatland area (Widayati and Suyanto 2013; Galudra et al. 2014).

(d) *Research should continue to provide technical and policy guidance on several key issues needed for the advancement of agroforestry in NDCs, including among others—domestication of potential tree species, improved germplasm, and potential impacts of climate change on the growing niches of tree species*: Agroforestry provides positive climate change adaptation services. However, this is likely to be affected by climate change and variability. Since agroforestry systems require a few years to become established and fully functional, this is concerning. More research is needed on climate change-adapted planting materials and understanding which agroforestry species may be more suited to future conditions in various field conditions that agroforestry could be implemented in.

(e) *Capacity building and dynamic partnerships are needed to overcome technological and investment challenges*: The investments required in early phases of agroforestry and in developing the necessary infrastructure for measurement, reporting and verification of the contributions of agroforestry to NDCs necessitates a different way of working to succeed. This new *modus operandi* needs to be inherently cross-sectoral given that agroforestry is neither forestry nor agriculture. It also calls for coinvestments from public, private, and civil society to enable it work. Stakeholders need to progress these innovative approaches for agroforestry to fulfill its major potential contribution to NDCs'.

(f) *Development of monitoring and reporting systems for agroforestry* that can contribute to NDC reporting systems as well as global stock takes under the Paris agreement is crucial. It would of course be a considerable help if consumer pressure to match their Individually determined contributions (IDCs) through demand for products from climate smart systems, such as agroforestry, would be more directly facilitated by recognizable (e.g. certified) market produce (van Noordwijk et al. 2022).

19.9 Policy Implications of the Key Issues Around Agroforestry Contribution to NDC Targets

The results of this study revealed the strong potential that agroforestry has to enhance the achievement of the unconditional targets of the NDCs of the aforementioned countries which have included agroforestry in their NDCs. However, for this potential to be realized on the ground, enabling contexts need to be facilitated. A few are listed below:

- Increased investments in tree planting material infrastructure and agroforestry knowledge systems are necessary to overcome current market deficiencies and technical knowledge shortfalls.
- Innovative blended financing mechanisms—including blending mitigation and adaptation finance, and impact investments, could facilitate rapid transformation through the effective implementation of agroforestry practices.
- Devising policy instruments that clarify tree tenure and carbon rights are fundamental to motivate local actors to implement agroforestry.
- Research should continue to provide technical and policy guidance on a number of issues needed for the advancement of agroforestry in NDCs, including domestication of potential tree species, improved germplasm, and potential impacts of climate change on the growing niches of tree species.
- Assessing the potential of agroforestry for consideration under REDD +.
- Capacity building and dynamic partnerships are needed to overcome technological and investment challenges.

References

Abatneh Y, Sahu O, Yimer S (2014) Purification of drinking water by low-cost method in Ethiopia. Appl Water Sci 4:357–362. https://doi.org/10.1007/s13201-013-0151-9

Akinnifesi FK, Sileshi G, Ajayi OC, Chirwa PW, Mng'omba S, Chakeredza S, Nyoka BI (2008) Domestication and conservation of indigenous Miombo fruit trees for improving rural livelihoods in southern Africa. Biodiversity 9:72–74

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99(1):15–27

Ammann M, Böll A, Rickli C, Speck T, Holdenrieder O (2009) Significance of tree root decomposition for shallow landslides. For Snow Landsc Res 82(1):79–94

Aponte C, García LV, Marañón T (2012) Tree species effect on litter decomposition and nutrient release in Mediterranean oak forests changes over time. Ecosystems 15(7):1204–1218

Chakeredza S, Hove L, Akinnifesi FA, Franzel S, Ajayi O, Sileshi G (2007) Managing fodder trees as a solution to human-livestock food conflicts and their contribution to income generation for smallholder farmers in Southern Africa. Nat Res Forum 31:286–291

Crossman ND, Bernard F, Egoh B, Kalaba F, Lee N, Moolenaar S (2016) The role of ecological restoration and rehabilitation in production landscapes: an enhanced approach to sustainable development. In: Working paper for the UNCCD Global Land Outlook

Dhyani SK, Ram A, Newaj R, Handa AK, Dev I (2020) Agroforestry for carbon sequestration in Tropical India. In: Ghosh P, Mahanta S, Mandal D, Mandal B, Ramakrishnan S (eds) Carbon

management in tropical and sub-tropical terrestrial systems. Springer, Singapore. https://doi.org/10.1007/978-981-13-9628-1_19
Dobie P, Sharma N (2014) Trees as a Global Source of Energy: from fuelwood and charcoal to pyrolysis-driven electricity generation and biofuels. World Agroforestry Centre, Nairobi
Duguma LA, Nzyoka J, Minang P, Bernard F (2017) How agroforestry propels achievement of nationally determined contributions. World Agrofor 34:1–8. https://www.worldagroforestry.org/publication/how-agroforestry-propels-achievement-nationally-determined-contributions
Egan PA, Chikoye D (eds) (2021) Harnessing nature-based solutions for smallholder plant health in a changing climate. SLU Global, Uppsala
Ellison D, Morris CE, Locatelli B, Sheil D, Cohen J, Murdiyarso D, Gaveau D et al (2017) Trees, forests and water: cool insights for a hot world. Glob Environ Chang 43:51–61
FAO (2015) Global forest resources assessment 2015: Desk reference. FAO, Rome
FAO (2017) The future of food and agriculture—trends and challenges. FAO, Rome
FAOSTAT (2021). Food and agriculture data. https://www.fao.org/faostat/en/#homen. Accessed 9 Nov 2021
Forest Carbon Partnership Facility (FCPF) (2018) Emission Reductions Program Document. Promoting REDD+ through Governance, Forest landscapes & Livelihoods in Northern Lao PDR
Franzel S, Carsan S, Lukuyu B, Sinja J, Wambugu C (2014) Fodder trees for improving livestock productivity and smallholder livelihoods in Africa. Curr Opin Environ Sustain 6:98–103. https://doi.org/10.1016/j.cosust.2013.11.008
Galudra G, van Noordwijk M, Agung P, Suyanto S, Pradhan U (2014) Migrants, land markets and carbon emissions in Jambi, Indonesia: land tenure change and the prospect of emission reduction. Mitig Adapt Strat Glob Chang 19(6):715–731
Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A, Bayala J et al (2010) Evergreen Agriculture: a robust approach to sustainable food security in Africa. Food Secur 2(3):197–214
Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc Natl Acad Sci 107(38):16732–16737. https://doi.org/10.1073/pnas.0910275107
Harrison RD, Thierfelder C, Baudron F, Chinwada P, Midega C, Schaffner U, den Berg J (2019) Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. J Environ Manage 243:318–330
Harvey CA, Villalobos JAG (2007) Agroforestry systems conserve species-rich but modified assemblages of tropical birds and bats. Biodivers Conserv 16:2257–2292. https://doi.org/10.1007/s10531-007-9194-2
Ilstedt U, Bargués Tobella A, Bazié H (2016) Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci Rep 6:21930. https://doi.org/10.1038/srep21930
Instituto Escolhas (2016) Quanto Custa Reflorestar 12 Milhões de Hectares? Instituto Escolhas, São Paulo
International Union for Conservation of Nature and Natural Resources—IUCN (2016) In: Moraes MA (ed) Forest landscape restoration in Brazil. Brasília, UICN
Jamnadass R, Place F, Torquebiau E, Malézieux E, Iiyama M, Sileshi GW, Kehlenbeck K, Masters E, McMullin S, Weber JC, Dawson IK (2013) Agroforestry, food and nutritional security. ICRAF Working Paper No. 170. World Agroforestry Centre, Nairobi. https://doi.org/10.5716/WP13054.PDF
Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agr Syst 76(1):1–10
Kristjanson P, Neufeldt H, Gassner A, Mango J, Kyazze FB, Desta S, Sayula G, Thiede B, Forch W, Thornton PK, Coe R (2012) Are food-insecure smallholder households making changes in their farming practices? Evidence form East Africa. Food Security 4(3):381–397. https://doi.org/10.1007/s12571-012-0194-z

Kuyah S, Sileshi GW, Nkurunziza L, Chirinda N, Ndayisaba PC, Dimobe K, Öborn I (2021) Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agron Sustain Dev 41(16). https://doi.org/10.10007/s13593-021-00673-4

Lasco RD, Delfino RJP, Espaldon MLO (2014) Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. Wiley Interdiscip Rev Clim Chang 5(6): 825–833

Leakey RRB, Sanchez PA (1997) How many people use agroforestry products? Agrofor Today 9(3):4–5

Lin BB (2007) Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric For Meteorol 144(1–2):85–94. https://doi.org/10.1016/j.agrformet.2006.12.009

Lin BB (2010) The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric For Meteorol 150(4):510–518

Liu G, Li J (2020) Research on the effect of tree barriers on rockfall using a three-dimensional discontinuous deformation analysis method. Int J Comput Methods 17(8). https://doi.org/10.1142/S0219876219500464

Liyama M, Neufeldt H, Dobie P, Njenga M, Ndegwa G, Jamnadass R (2014) The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. Curr Opin Environ Sustain 6:138–147

Ma B, Yu X, Ma F, Li Z, Wu F (2014) Effects of crop canopies on rain splash detachment. PLoS One 9(7):e99717. https://doi.org/10.1371/journal.pone.0099717

Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014a) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr Opin Environ Sustain 6:8–14

Mbow C, Van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014b) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67

Minang PA, Duguma LA, Bernard F, Mertz O, van Noordwijk M (2014) Prospects for agroforestry in REDD+ landscapes in Africa. Curr Opin Environ Sustain 6:78–82

Mulia R, Nguyen DD, Nguyen MP, Steward P, Pham VT, Le HA, Rosenstock T, Simelton E (2020) Enhancing Vietnam's nationally determined contribution with mitigation targets for agroforestry: a technical and economic estimate. Landarzt 9:528. https://doi.org/10.3390/land9120528

Muthee K, Duguma L, Nzyoka J, Minang P (2021) Ecosystem-based adaptation practices as a nature-based solution to promote water-energy-food nexus balance. Sustainability 13:1142. https://doi.org/10.3390/su13031142

Muthee K, Duguma L, Wainaina P, Minang P, Nzyoka J (2022) A review of global policy mechanisms designed for tropical forests conservation and climate risks management. Front For Glob Change 4:748170. https://doi.org/10.3389/ffgc.2021.748170

Nair PKR, Nair VD, Kumar BM, Showalter JM (2010) Chapter Five—Carbon sequestration in agroforestry systems. In: Sparks D (ed) Advances in Agronomy, vol 108. Academic Press, San Diego, CA, pp 237–307. https://doi.org/10.1016/S0065-2113(10)08005-3

Nath AJ, Lal R, Sileshi GW, Das AK (2018) Managing India's small landholder farms for food security and achieving the "4 per Thousand" target. Sci Total Environ 634:1024–1033. https://doi.org/10.1016/j.scitotenv.2018.03.382

Nath AJ, Sileshi GW, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J Clean Prod 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831

NDC Registry. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx

Njenga M, Mendum R, Gitau J, Iiyama M, Jamnadass R, Watson C (2017) Trees on farms could satisfy household firewood needs. Tree Farmers Mag Afr 33(16):20–23

Oino P, Mugure A (2013) Farmer-oriented factors that influence adoption of agroforestry practices in Kenya: Experiences from Nambale District, Busia County. Int J Sci Res 2(4):450–456

Palm CA, Woomer PL, Alegre JC, Arevalo L, Castilla CE, Cordeiro DG, Feigl B, Hariah K, Kotto-Same J, Mendes A, Moukam A, Murdiyarso D, Njomgang R, Parton WJ, Ricse A, Rodrigues V, Sitompul SM, van Noordwijk M (2000) Carbon sequestration and trace gas emissions in slash and burn and alternate land uses in the humid tropics. In: Sanchez PA, Ericksen PJ, Juo ASR (eds) Alternatives to slash and burn agriculture: a global synthesis. American Society of Agronomy Special Publication, Madison, WI

Place F, Roothaert R, Maina L, Franzel S, Sinja J, Wanjiku J (2009) The impact of fodder trees on milk production and income among smallholder dairy farmers in East Africa and the role of research. ICRAF Occasional Paper No. 12. World Agroforestry Centre, Nairobi

Pumariño L, Sileshi GW, Gripenberg S, Kaartinen R, Barrios E, Muchane MN, Midega C, Jonsson M (2015) Effects of agroforestry on pest, disease and weed control: a meta-analysis. Basic Appl Ecol 16:573–582. https://doi.org/10.1016/J.BAAE.2015.08.006

Reang D, Hazarika A, Sileshi GW, Das AK, Nath AJ (2021) Assessing tree diversity and carbon storage during land use transitioning from shifting cultivation to indigenous agroforestry systems: Implications for REDD+ Initiatives. J Environ Manage 298. https://doi.org/10.1016/j.jenvman.2021.113470

Sanchez P (2000) Linking climate change research with food security and poverty reduction in the tropics. Agric Ecosyst Environ 82:371–383

Schoeneberger MM (2009) Agroforestry: working trees for sequestering carbon on agricultural lands. Agr Syst 75:27–37

Schoeneberger M, Bentrup G, de Gooijer H, Soolanayakanahally R, Sauer T, Brandle J, Zhou X, Current D (2012) Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. J Soil Water Conserv 67(5):128–136. https://doi.org/10.2489/jswc.67.5.128A

Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, Turner B (2020) Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos Trans R Soc Lond B Biol Sci 375(1794):20190120. https://doi.org/10.1098/rstb.2019.0120

Siegele L (2020) BRIEF: Gender equality and women's empowerment in updated and New Nationally Determined Contributions (NDCs). https://wedo.org/wp-content/uploads/2020/12/GenderNDCs_FINAL_Dec2020.pdf. Accessed 9 Nov 2021

Sileshi G, Schroth G, Rao MR, Girma H (2008) Weeds, diseases, insect pests and tri-trophic interactions in tropical agroforestry. In: Batish DR, Kohli RH, Jose S, Singh HP (eds) Ecological basis of agroforestry. CRC Press, pp 73–94

Sileshi GW, Mafongoya PL, Akinnifesi FK, Phiri E, Chirwa P, Beedy T, Makumba W, Nyamadzawo G, Njoloma J, Wuta M, Nyamugafata P, Jiri O (2014) Fertilizer trees. In: Encyclopedia of agriculture and food syste*ms*, vol 1. Elsevier, San Diego, pp 222–234

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Howden M, McAllister T, Pan G, Romanenkov V, Schneider U, Towpravoon S, Wattenbach M, Smith J (2008) Greenhouse gas mitigation in agriculture. Philos Trans R Soc B Biol Sci 363(1492):789–813. https://doi.org/10.1098/rstb.2007.2184

Tubiello FN, Salvatore M, Cóndor Golec RD, Ferrara A, Rossi S, Biancalani R, Federici S, Jacobs H, Flammini A (2014) Agriculture, forestry and other land use emissions by sources and removals by sinks, Rome, Italy

UNFCCC (2021) Updated NDC Synthesis Report: Worrying Trends Confirmed. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx. Accessed 26 Oct 2021

USAID (2015) Sector environmental guidelines: forestry. https://www.usaid.gov/sites/default/files/documents/1860/SectorEnvironmentalGuidelines_Forestry_2015.pdf

USDA National Agroforestry Centre (2015) How can agroforestry help landowners adapt to climate change? Working Paper series 2015. https://www.fs.usda.gov/nac/documents/workingtrees/infosheets/WTInfoSheet-ClimateAdaptation.pdf

Van Noordwijk M (2019) Integrated natural resource management as pathway to poverty reduction: innovating practices, institutions and policies. Agr Syst 172:60–71

Van Noordwijk M, Roshetko JM, Angeles MD, Fay C, Tomich TP (2008) Farmer tree planting barriers to sustainable forest management. In: Smallholder tree growing for rural development and environmental services. Springer, Dordrecht, pp 429–451

van Noordwijk M, Hairiah K, Lasco R, Tata HL (2019) How can agroforestry be part of disaster risk management? In: van Noordwijk M (ed) Sustainable development through trees on farms: agroforestry in its fifth decade. World Agroforestry (ICRAF), Bogor (Indonesia), pp 215–222

van Noordwijk M, Leimona B, Pham TT, Duguma LA, Dewi S, Minang PA (2022) Carbon footprints, informed consumer decisions and shifts towards responsible agriculture, forestry and other land uses? Carbon Footprints 1:4. https://doi.org/10.20517/cf.2022.02

Verchot LV, van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anumpama KV, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strat Glob Chang 12(5):901–918

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) (2000) Land use change and forestry. Cambridge University Press, Cambridge, p 375

West PC, Gibbs HK, Monfreda C, Wagner J, Barford CC, Carpenter SR, Foley JA (2010) Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. Proc Natl Acad Sci 107(46):19645–19648

Wheeling K (2019) How forest structure influences the water cycle. Eos 100. https://doi.org/10.1029/2019EO134709

Widayati A, Suyanto S (eds) (2013) emission reduction efforts in Jambi: towards nesting approach—Substantive Report of REALU II Indonesia. World Agroforestry Centre—ICRAF Southeast Asia Regional Program, Bogor, Indonesia. http://apps.worldagroforestry.org/sea/Publications/files/report/RP0297-14.pdf

Xie C, Cai S, Yu B, Yan L, Liang A, Che S (2020) The effects of tree root density on water infiltration in urban soil based on a Ground Penetrating Radar in Shanghai China. Urban For Urban Greening 50:126648. https://doi.org/10.1016/j.ufug.2020.126648

Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. Working Paper 179. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Bogor, Indonesia

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. Sci Rep 6:29987. https://doi.org/10.1038/srep29987

Zomer RJ, Bossio DA, Trabucco A, van Noordwijk M, Xu J (2022) Global carbon sequestration potential of agroforestry and increased tree cover on agricultural land. Circ Agr Syst 2:3. https://doi.org/10.48130/CAS-2022-0003

Chapter 20
Potential of Traditional Agroforestry Systems for Intensification of Agriculture and Meeting Global Goals: Lessons from Asia and Africa

Jayshree Shukla and Shalini Dhyani

Abstract The role of traditional agroforestry systems in enhancing ecosystem productivity and protecting natural resources has been explored during the last four decades. Research efforts have established the potential of traditional agroforestry as a solution for sustainable intensification of agriculture to meet the increasing food production demands and ecosystem benefits. The least developed, as well as rapidly developing countries across Asia and Africa currently face diverse socio-economic challenges due to the burgeoning human population, poverty, hunger, and unsustainable agricultural systems. With the need to sustain the demands of exponential population growth without compromising the natural resources base, sustainable agriculture intensification based on agroforestry has gained momentum. There are efforts to mainstream the benefits of ecological-intensifying agriculture to provide food, nutritional, environmental, and livelihood security by enhancing ecosystem services and restoring biodiversity. However, socioeconomic constraints like limited understanding and awareness, lack of implementation, commercialization of agriculture, interactive governance and policy concerns, etc. have led to the decline of traditional agroforestry practices across African and Asia countries. The present chapter highlights the potential of traditional agroforestry practices for sustainable agriculture intensification in African and Asian regions and their relevance to achieving ecosystem restoration, conservation, sustainable development, and climate targets. Agroforestry systems have proved to increase agriculture productivity while minimizing carbon footprint, in line with the UN Sustainable Development Goals (SDGs) and the ecological restoration agenda of the UN Decade (2021–2030).

Keywords Land degradation · Sustainable land management · Monocropping · Sustainable development goals · Land degradation neutrality · Climate change

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20.1 Introduction

According to the report of the Intergovernmental Panel on Climate Change, climate change is widespread, rapid, and intensifying (IPCC 2019, 2021). The growing climate variability and land degradation have severe impacts on plant growth and sustenance due to elevated carbon dioxide levels, rising temperatures, change in precipitation rates, and the occurrence of extreme events in short intervals is leading to negative impacts on food and fiber production (Lobell et al. 2011; Ortiz-Bobea et al. 2021). Land degradation exacerbates the food deficit due to its effect on agricultural systems leading to reduced productivity simultaneously impacting livelihoods, on-farm income, and development dependent on agriculture in most developing and low-income countries (Mbow et al. 2014a; Rojas-Downing et al. 2017). Incorporating trees into land-use systems has been emphasized in the ongoing discussions over agriculture sustainability highlighting the importance of diversification to improve land and crop management (Garnett et al. 2013; Cassman and Grassini 2020).

There are various ways to accomplish sustainable agricultural goals by combining greater yields with ecosystem services; however, there are limited approaches that concurrently improve agroecosystem diversity and farm production. Traditional Agroforestry Systems (AFS), which combines the production of trees and crops within the same unit of land, is among the most diverse types of agriculture systems within that physical and social geography (Waldron et al. 2017; Brown et al. 2018). Even though AFS have long been studied for its ecological advantages and peasant-farmer relationships, scientific data now shows that it can enhance crop yield by two orders of magnitude (an approximate 96% in a multistudy analysis) (Pretty and Bharucha 2014; Pretty et al. 2018), based on crops grown, weather patterns, and skillset (Altieri and Nicholls 2020). Between reforestation and agricultural land use, agroforestry has been identified as a more feasible alternative as it facilitates carbon storage, enhances productivity, and is proven to be highly sustainable as it enhances soil fertility and restores degraded lands (Leakey 2014; Shrestha et al. 2018; Rose et al. 2019; van Noordwijk et al. 2021). AFS that require very low input, have high recycling rates, and appropriate integration of trees, crops, and livestock, as viable contenders for the accomplishment of both climate change targets and sustainable livelihood (Koohafkan et al. 2012). Studies suggest that building resilient agroecological systems (Mahmud et al. 2021) with enhanced socioecological functions and adaptive abilities have multiple cobenefits that include improved carbon sequestration, climate adaptations and mitigations (Shi et al., 2018; Gaffney et al. 2019; Ayantunde et al. 2020; Dhakal and Rai 2020; Awazi et al. 2021).

The Food and Agriculture Organization (FAO) has addressed the need to reform food and agricultural systems in line with Agenda 2030 and the UN Sustainable Development Goals (SDGs) that suggests that agro-ecological projects might help with this endeavor (Pretty et al. 2018). Land-use change, loss of soil fertility and productivity, has negative impacts on the livelihoods of millions of people dependent on agriculture and pastors, especially in countries affected by food insecurity and droughts. Unplanned expansion and lack of sustainable management of grazing fields and croplands has direct linkages with the rapid land degradation, mainly in dryland areas. This has led to the introduction of the Land Degradation Neutrality (LDN) concept as a target of “no net loss” for SDG 15- Life on Land and has been adopted by UNCCD (UNCCD 2016; Cowie et al. 2018) as a goal to revert/reduce land degradation. Intensification of conflicts for land, access to water resources and grazing grounds as a result of exacerbated climate change leading to erratic seasonal variations, longer drought periods, etc. have called for community-based technologies in Sustainable Land Management. These techniques have the potential to enhance land productivity, vegetation cover, and carbon stocks, using very insufficient resources for providing large contributions to achieve LDN targets and addressing land degradation. These sustainable approaches, particularly the ones using mixed land use with agroforestry have proved to be of greater benefit in terms of achieving LDN targets (Brown et al. 2018).

This research aims to investigate the potential of agroforestry for delivering sustainable intensification of agriculture for food and environmental security. The aim of this chapter is to review the existing information as well as to identify relevant research routes for exploring and analyzing the potential contribution of AFS to sustainable agricultural production and address climate challenges in both Asian and African countries.

20.2 Traditional Agroforestry Systems and Practices in Asia and Africa

Agroforestry has been practiced for a long time in Asian, African, and Latin countries and has been improved as per the required conditions and subsequent land degradation challenges. In Africa, the growing population poses greater threats to food security and hunger along with the impending climate change risks (Dhyani et al. 2021). These impending challenges have been faced due to shifting from sustainable farming systems and land restoration measures such as traditional AFS to monocropping and agriculture intensification in Africa. Asian countries have long histories of adopting diverse agroforestry practices as adaptation and mitigation measures across varied ecological and climatic zones (Kumar et al. 2012). Countries in the Asia-Pacific region like India, China, Australia, Indonesia, etc. have been focusing on silvopastoral systems with more than 60% research on agroforestry practices in this region as documented by Shin et al. (2020). The major AFS prevalent across Asia include scattered trees on pasture lands (in dry regions); home gardens, multistoried plantation-based systems and hedge-row cropping in humid regions; shelter belts and traditional shaded coffee agroforests in semiarid regions; while in Africa parklands and silvopastoral systems along with improved fallows and indigenous fruit-trees -based systems are quite prevalent. There are many common AFS being followed traditionally in both regions but have turned out differently in the present circumstances due to varied socioecological pressures.

20.2.1 Significance of Agroforestry Practices for Asia

Since ancient times, traditional agroforestry practices have been a major part of Asian agriculture regimes throughout India, Indonesia, Malaysia, Bangladesh, and Sri Lanka (Dagar et al. 2014; Khan et al. 2021). Approximately 3% of the geographical area in Southeast Asia holds 8.5% of the world's total population. The region contains the world's 7.9% agricultural base, being home to the globe's major agroforests on 28.9% of the agricultural land having 30% of tree cover (van Noordwijk et al. 2020). The South and Southeast Asian region is considered the cradle of AFS with a long history and an array of AF practiced under diverse agro-ecological conditions (Kumar et al. 2012). Agroforestry techniques have improved over time in the region in order to meet requirements of provisioning as well as regulating ecosystem services, largely encompassing "*forest transition phases*" in the landscape (Kumar et al. 2012). Traditional AFS such as home gardens are quite common across the Asia Pacific region providing a variety of ecological functions by contributing toward food security, soil fertility, improving habitat conditions, and lowering temperatures which are important to combat climate change (Waldron et al. 2017). These traditional agroforestry regimes have proved to be of greater relevance in the present decade of ecosystem restoration by the UN that can largely help to address the loss of biodiversity due to impending climate change. However, the introduction of nonnative cash crops has led to the paradigm shift resulting in conversion and loss of these traditional land-use systemsDagar et al. 2014) (Fig. 20.2).

Expanding population and increasing food insecurity has led to the dominance of monoculture production systems particularly in favor of species that are more commercial in nature which has also been depicted in the forest and agricultural policies in the past, leading to the decline in AFS across Asia (Liu et al. 2018) (Fig. 20.1).

The commercial viewpoint of agriculture production has resulted in alteration of natural patterns and biotic interactions giving rise to new challenges of land degradation and mismanagement (Rickards and Howden 2012; Dagar et al. 2020). These challenges have led to the transition toward the research and development in the traditional agroforestry patterns and their improvement for sustainable land use (Geiger 2015). Table 20.1 shows the percentage of tree cover in agricultural lands in different parts of Asia for the years 2008–2010 along with the millions of people living in the agricultural landscapes, with the highest population seen in Southeast Asia (Zomer et al. 2014). Studies have suggested that the South Asian peninsula will suffer greater pressure of the impacts of climate change, beginning with frequent droughts and changes in rainfall patterns along with higher temperatures which will undoubtedly affect the agriculture output and livelihood of the farmers (Mendelsohn

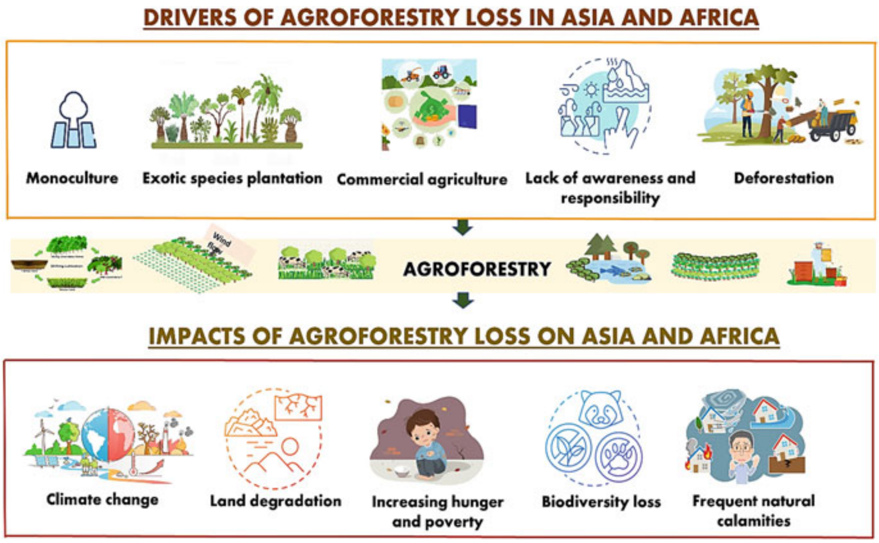

Fig. 20.1 Drivers of loss of traditional agroforestry systems and its larger socioecological and economic impacts on marginalized communities residing in Asia and Africa

2014; Ahmad et al. 2020). The ability of traditional AFS to tolerate and survive extreme weather events has been recognized to counteract the negative impacts of climate change in Asia (Aryal et al. 2019).

There has been a huge interest in AFS across Asia and Asia-Pacific Agroforestry Network (APAN) formulation started sometime during the 19th FAO Regional Conference for Asia and the Pacific in the year 1988. Agriculture and Forestry ministers endorsed the formation of a regional initiative in agroforestry to address marginal lands, marginal people, shifting cultivation, and sustainable development as three sets of pressing problems, and this in this way first regional agroforestry network was established.

The carbon sinks produced by incorporating trees into agriculture can be utilized as carbon credits, creating a constant income source for the rural communities and helping protect natural forests. Reducing Emissions from Deforestation and forest Degradation (REDD+) policies have been a major part of the global climate discourse since 2007. These policies have resulted in the incorporation of the Agriculture, Forestry, and Other Land Use (AFOLU) sector in the national framework for reducing the risks of climate change (van Noordwijk 2020). The AFOLU sector is a major contributor to Greenhouse Gas emissions in the Asian peninsula and is further projected to increase with land-use change and increasing food production (Pradhan et al. 2019).

The REDD+ policies have motivated the countries to improve forest health and submit their Nationally Determined Contributions (NDCs) in accordance with the Paris Agreement of lowering carbon emissions and making it a national priority (Duguma et al. 2017). These goals can be achieved through the incorporation of

Table 20.1 The extent of agroforestry cover in different parts of Asia showing the percentage of agricultural land (2008–2010), along with the population (in millions) residing in the landscapes having more than 10%, 20%, and 30% of tree cover (2008–2010)

Tree cover (%)	>10%		>20%		>30%	
Region	Agricultural land (%)	Population (%)	Agricultural land (%)	Population (%)	Agricultural land (%)	Population (%)
Northern and Central Asia	25.3	23	9.7	7	4.3	3
South Asia	27.7	34	7.8	8	3.6	2
Southeast Asia	79.6	73	62.9	46	49.9	30
East Asia	47.5	57	22.1	21	11.8	8
Global	43.4	46	23.1	19	17.0	10

Source: Zomer et al. (2009, 2014)

agroforestry in their NDCs and especially for the Non-Annex I nations (particularly prone to the harmful effects of climate change as identified by UNFCCC) (Chavan et al. 2021). At a rate of 21%, Asian countries have included agroforestry in their NDCs, significantly lower than the 71% and 34% commitment by the African and American countries, respectively (Rosenstock et al. 2019). In order to attain the committed goals, Asian countries need to take solid measures to recover and improve deteriorated AFS with the use of the traditional knowledge and expertise required to maintain the AFS momentum of the region. Significant steps are required to be taken in order to improve agricultural productivity and enhance livelihood opportunities for marginalized communities, small-scale farmers, and pastoralists through improved techniques, innovations, and sustainable agriculture intensification.

20.2.2 Significance of Agroforestry for Africa

Traditional agroforestry systems are of great importance for sub-Saharan Africa (SSA) as they cover the major agricultural landscapes and provide critical ecosystem services like food, fodder, fuelwood, etc. for the sustenance of local livelihoods. Rural African households are primarily dependent on agriculture through small-scale processing, farming, livestock rearing, wage labor, trading, and provision of services (Panel 2013; Kuyah et al. 2019). More than 90% of the rural households have been found to be directly dependent on agriculture in a study by Davis et al. (2017), taking into account 22 African countries. Traditional AFS contributes toward the sustenance of livelihoods through the production of food, provision of fuelwood, income generation, as well as through Non-Timber Forest Products (NTFPs) such as medicines, food derivatives, oils, gums and resins, bamboo, and other species for construction, handicraft productions as well as livelihood benefits (Kuyah et al. 2016, 2017).

However, in Africa, prevalent farming practices and agriculture intensification have led to biodiversity and soil quality decline accompanied by severe land degradation and environmental pollution causing food insecurity and poverty (Mueller et al. 2012). This degradation and food deficit have been associated with the yield gap observed in the region. The increasing population residing in the agricultural landscapes in SSA as shown in Table 20.2 along with the minimal percentage of tree cover in agricultural land in North Africa/ Western Asia shows the indifference of farmers toward incorporating agroforestry in their farmlands. Monocropping systems have replaced the traditional crop patterns leading to low yield and stagnant cereal production (during the 1990s), often attributed to the low fertilizer use (5–8 kg ha^{-1}) than India (10–110 kg ha^{-1}) and China (10–240 kg ha^{-1}) (Carsan et al. 2014). The use of fertilizers in agriculture to increase yield has however shown to cause the decline in biodiversity.

Traditional AFS in Africa includes coffee, cocoa, and rubber and happens to be great habitat for the African biodiversity (Clough et al. 2011). These studies have

Table 20.2 Extent of agroforestry cover in different parts of Africa showing the percentage of agricultural land (2008–2010), along with the population (in millions) residing in the landscapes having more than 10%, 20%, and 30% of tree cover (2008–2010)

Tree cover (%)	>10%		>20%		>30%	
Region	Agricultural land (%)	Population (%)	Agricultural land (%)	Population (%)	Agricultural land (%)	Population (%)
North Africa /Western Asia	11.0	13	5.5	4	3.3	2
Sub-Saharan Africa	30.5	39	15.0	16	8.4	7
Global	43.4	46	23.1	19	17.0	10

Source: Zomer et al. (2009, 2014)

provided a base for further improvement in finding a balance between yield and biodiversity through efficient management systems especially in small farms (Carsan et al. 2013).

The lack of clarity about the benefits of biodiversity among the stakeholders and policymakers in Africa and the need to generate maximum possible outputs from small pieces of land, has led to the loss of native species and presence of commercial agriculture than diverse traditional multicropping practice (Zomer et al. 2014; Leakey 2017) (Fig. 20.1). Traditional AFS have been reported to lose their diverse tree species due to increasing industrialization and reductionist approaches for example, in East Africa and Ghana where declining agroforests are observed due to the reduction in available land and consistent pressure to improve yield patterns by using fertilizers and replacement by commercial but low-density species (Isbell et al. 2011; Rosa-Schleich et al. 2019). There is evidence that the traditional approaches of diversified agroforestry practices can be means to conserve resources along with increasing the farm yield. These systems can have a positive impact on soil quality, water retention capacity and nutrient cycling, thus helping to close the yield gap and promote better livelihood opportunities in Africa (Zerihun 2021). Practices that involve a combination of species such as intercropping or rotation improve the soil quality by enhancing nitrogen fixation along with the production of manure containing organic matter and thus reducing the reliance on fertilizers (Mbow et al. 2014b). Agroforestry's potential for boosting production, promoting ecosystem services, and offering adaptation in varied African farm contexts will require more research by integration of ecological knowledge with an awareness of social-economic limitations (Kuyah et al. 2020).

20.3 Agroforestry to Achieve UN Sustainable Development Goals (SDGs)

AFS provides a multifunctional alternative to conventional agriculture techniques which have several negative implications on natural resources and the environment. This is in line with the current Sustainable Development Goals laid out by the UN, which have woven together several targets like food security, climate, socioecological, and environmental restoration (Orr and Mwale 2016; Brown et al. 2018). These goals can be achieved through proper implementation and development of AFS as an alternative to sustainable land utilization beginning with the SDG 2 of food security, i.e., by increasing agriculture productivity (Blesh et al. 2019). AFS provides resilience toward impending climate risks and poverty by increasing water storage and infiltration rates while balancing the evaporation rates, thus, in turn, securing agriculture productivity and contributing to the SDGs (Garrity et al. 2010; Pandey et al. 2017) (Fig. 20.2).

An increase in yield and overall farmer income during less productive cropping season through tree-based farm productions has been observed during several

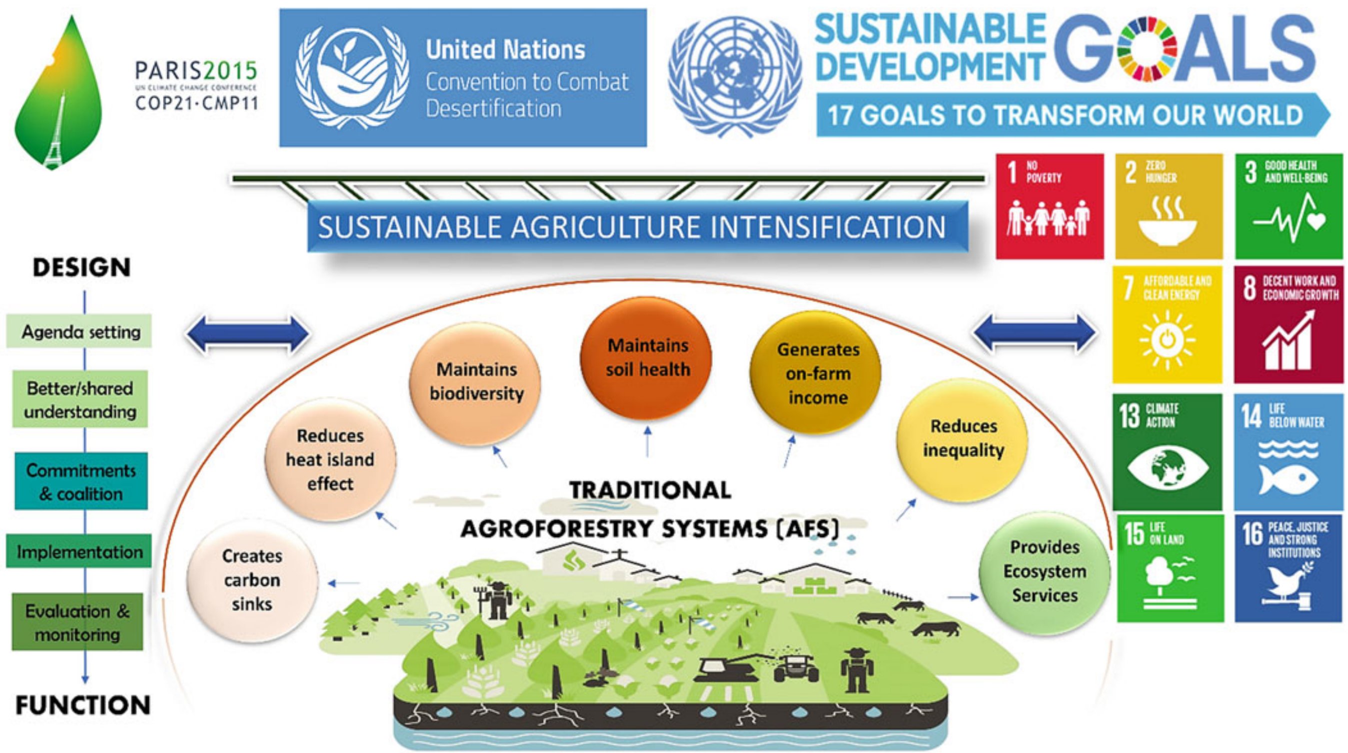

Fig. 20.2 Agroforestry as a multifunctional approach for sustainable agriculture intensification and achievement of international targets for biodiversity, restoration, and climate change

studies thus proving to be a viable source of income through the provision of services by the trees on farm (Charles et al. 2013; Miller et al. 2017). These unrestricted flow of ecosystem services generate livelihood resilience in line with other sustainable development goals such as SDGs 1 (reducing poverty by generating another source of income); SDG 7 for providing energy security through farm-based income and easily available fuelwood (Sharma et al. 2016), SDG 3 (promoting health and well-being by providing readily available fuel and fodder thus saving on time and energy to walk long distances), followed by SDG 8, 10 and 16 by increasing resilience toward market fluctuations and reduced dependence on supply chain actors which is beneficial particularly in the case of small land and pasture owners by providing them equity and dignity in the developing world thus creating an inclusive society for sustainable development (Cook et al. 2015).

AFS also provide a wide range of environmental benefits in line with SDG 13 of climate action by inducing crop resilience toward climate change through increasing water infiltration rates, combating extreme temperatures, preventing soil erosion; and SDG 15 by improving life on land through ecosystem restoration and sustainable use of wild resources. It enhances ecosystem productivity, landscape connectivity, carbon sequestration potential of farmlands through the incorporation of diverse tree species and reducing the pressure on natural forests (Mbow et al. 2014a; Zomer et al. 2016; Salvini et al. 2016). Agroforestry practices can also help in achieving other international goals such as Land Degradation Neutrality (LDN) which aims to conserve, sustainably manage and restore degraded land with targets adopted at local as well as national scale (Fig. 20.2). These targets can be achieved through agroforestry as the inclusion of trees in farms increases land productivity by enhancing nitrogen fixation, soil stabilization, and controlling soil erosion. Landscape and forest restoration to cover the loss of past and present human encroachments can be achieved through agroforestry solutions by providing permanent tree cover and several other economic benefits (Nzyoka et al. 2018).

20.4 Advances and Opportunities

Agroforestry has been increasingly recognized as a multidimensional pathway toward the achievement of numerous environmental and socioecological challenges in both Asia and Africa (van Noordwijk et al. 2019; Kuyah et al. 2020). Removing the institutional hurdles rather than controlling agroforestry innovation under a single polycentric umbrella is a major step toward motivating more local-level developments and creating synergies between agriculture and forestry. The scaling of agroforestry to a regenerative as well as sustainable approach delivering food sovereignty and enhanced ecosystem services requires improvement of agroecological principles, acknowledging native experience and the interconnectedness of each system with one another along with their multifunctionality at regime level (Geels and Kemp 2007; Buttoud et al. 2013; Nicholls et al. 2016). Switching to sustainable natural agriculture that contributes to a sustainable world would need not just a modification to the current production system, but also a transition. Such a change might be made possible by new agricultural performance approaches based on agroecological concepts (Nicholls et al. 2016). There is a need for innovation in agriculture practices globally in order to address food security, which can be achieved through encouraging functional diversity in species and inclusion of perennial crops at local as well as regional scales (Tittonell et al. 2016).

Agroforestry practices have shown to have high-yielding benefits which have been increasingly recognized and these techniques have been adopted for the restoration of low-yield lands through the introduction of trees (Garrity et al. 2010; Zomer et al. 2016). There are many conditions where agroforestry options are not feasible for an application like the inability of small farmers to afford a steady supply of inputs in remote areas or land where the introduction of new trees is not possible (IFAD/UNEP 2013). However, in a multifocal framework, there are several other approaches to sustainably utilize the landscape and thus an approach suitable for appropriate land conditions can be implemented rather than reverting to the conventional approaches (Pingali et al. 2016; International Panel of Experts on Sustainable Food Systems 2016). More focus should be given to the underutilized native species widening the scope of inclusion of plants and animals, along with incorporating microorganisms as a part of agroforestry systems by creating pest-suppressive and climate-smart landscapes. Now, is the time to realign both strategy and funding to better represent an acceptable balance of agricultural alternatives in a multigoal framework. Such a shift would bring significant new investments, innovation, and organizational advances to less-mainstream systems like agroforestry, boosting yields upward. We might drastically enhance international targets on food security, social well-being, and ecological sustainability by recognizing and tapping on this potential, as we have pledged to do under the SDGs.

SAARC countries in Asia have recently developed a coalition called South Asia Association for Regional Cooperation (SAARC)'s Regional Coordinated Programme on Agroforestry (SARCOPA) for promoting AFS across S. Asia. India has been a pioneer in developing the National Agroforestry Policy in 2014 to fast-track agroforestry adoption and expansion and to remove the strict rules against felling and transporting trees. For 2016–2020, India already committed $410 million to implement the agroforestry policy and policy-supported agroforestry is to be included for funding through the Corporate Social Responsibility mechanism (3.5 billion annual investment) through this policy. This has further facilitated National agroforestry policy development by Nepal and other S. Asian countries. Similar efforts in Africa can be helpful. Reversing Land Degradation project in Africa, funded by European Union has an explicit policy objective to scale-up Evergreen Agriculture (Re-greening Africa, 2017–2022) as an active intervention to use agroforestry for sustainable land restoration across eight African countries (Kenya, Rwanda, Ethiopia, Somalia, Niger, Mali, Senegal, and Ghana). It is relevant to mention that successful acceptance of AFS is not only dependent on developing appropriate technical approaches but also on framing an enabling legal, political and official atmosphere to reinforce the scaling-up procedure.

20.5 Limitations and Constraints

Historical, economical, and biophysical considerations are the primary constraints for mainstreaming, up-scaling, and out-scaling agroforestry practices in the fast-developing world (Sood and Mitchell 2009; Brown et al. 2018). The historical constraints include industrial agricultural growth centered on output maximization of high-input monocrops, frequent use of hybrid crops for enhanced productivity in past five decades. This is typically accomplished by completely separating trees and crops. There is almost no place for other plants, much less even in high-diversity systems, when the goal is to increase the yield of particular crops. This trend continues, and is clear by the strong drive for rubber and Palm Oil monocultures in Asia, cocoa monocultures in Ghana, and coffee monocultures in Latin America (van Noordwijk et al. 2012; Muschler 2016). Wages and salaries for sowing and growing trees, lesser performance of the staple feedstock, poor farmland security, farmer mobility, fewer entitlements over the use of the trees planted, lack of knowledge about compatible trees, along with insufficient financial compensations for diversified tree crops and generation of resources are some of the causes of low interest in planting trees. In the tropics, these limits are prevalent in various mixed cropping practices. Higher labor requirements for pruning and biomass recycling and prolonged benefits from the trees, which might take more than a decade to reach market-readiness, are the primary socioeconomic obstacles to agroforestry success (Minang et al. 2014).

The key biophysical restriction for agroforestry is that excessive shading by trees can significantly impair the output of sun-demanding crops. This problem may be reduced or even eliminated by proper tree selection, management (e.g., pruning and lopping), as well as crop species and types that can bear additional shading. With recent concerns about environmental degradation caused by high-input monocultures and commodity price volatility, production objectives are broadening to include income diversification, resulting in increased stability, as well as increased ecological resistance, the resilience of systems to pests, diseases, and climatic extremes (Liu et al. 2018). Biological inputs and services are increasingly been examined as alternatives to chemical inputs in natural agriculture or low-input sustainable agriculture technologies. This effort is particularly important in developing nations with limited financial resources in Asian and African countries. Exploration, identification, and mass propagation of the most appropriate plants are critical in order to create the most successful systems (Kiyani et al. 2017; Brown et al. 2018).

Other constraints for the adoption of agroforestry systems include lack of skills, poor yield especially due to infertile soil, and lack of innovation in farming techniques due to lack of awareness in order to improve output. By taking solid steps to incentivize and provide subsidies to farmers for adopting agroforestry systems, regular training and hands-on experience to the young farmers and involving them in policy creation would prove instrumental in creating agroforestry as a base for sustainable land-use intensification in the continents right from the grass-root level.

Ground water dependence is another issue that needs to be addressed in Asian and African context to find options and irrigation alternative by promoting precision irrigation and agriculture in the region that is already facing shortage of water and rapid decline is inevitable in coming years. One of the important and crucial aspect is addressing land rights and also enhancing interactive governance to facilitate interest among communities for AFS. Lack of felling and timber selling rights have been a major deterrent among communities for promoting AFS and with rights communities will be interested to scale up and out traditional AFS for agroforestry benefits.

20.6 Conclusions

African and Asian countries have been practicing traditional agroforestry practices for several decades. There are many similarities in the AFS practiced across both continents as land degradation is a common problem faced here due to the increasing demand-supply gap. Local farmers and small landholders in the region are equipped with vast knowledge about the crop-forest-wildlife integration and the conditions on-farm, their understanding of the AFS needs to be touched upon by the local governance by linking traditional and indigenous knowledge systems with scientific innovations for addressing biodiversity, land degradation, restoration, climate, and sustainability concerns in the region. The national governments need to mainstream traditional AFS in their strategies and frameworks to address the constraints on the grass-root level and create synergy with international sustainability, biodiversity, climate, and restoration targets and goals. Given the dependency of the path for current institutional frameworks, debate alone is not going to change the scenario. Change requires a top-down approach that insists on functions rather than forms. This includes real progress to sustainably manage and develop rural landscapes with persistent poverty that requires new approaches including rights, incentives, technological inputs, and human capacity to support new-age agroforestry practices.

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References

Ahmad F, Uddin MM, Goparaju L, Rizvi J, Biradar C (2020) Quantification of the land potential for scaling agroforestry in South Asia. KN J Cart Geogr Inf 70:71–89

Altieri MA, Nicholls CI (2020) Agroecology: challenges and opportunities for farming in the Anthropocene. Ciencia e investigación agraria 47(3):204–215

Aryal JP, Sapkota TB, Khurana R, Khatri-Chhetri A, Jat ML (2019) Climate change and agriculture in South Asia: adaptation options in smallholder production systems. Environ Dev Sustain 9:1–31
Awazi NP, Tchamba MN, Temgoua LF, Tientcheu-Avana ML (2021) Agroforestry as an adaptation option to climate change in Cameroon: assessing farmers' preferences. Agric Res 10:1–2
Ayantunde AA, Oluwatosin BO, Yameogo V, van Wijk M (2020) Perceived benefits, constraints and determinants of sustainable intensification of mixed crop and livestock systems in the Sahelian zone of Burkina Faso. Int J Agric Sustain 18(1):84–98
Blesh J, Hoey L, Jones AD, Friedmann H, Perfecto I (2019) Development pathways toward "zero hunger". World Dev 18:1–4
Brown SE, Miller DC, Ordonez PJ, Baylis K (2018) Evidence for the impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in high-income countries: a systematic map protocol. Environ Evid 7(1):1–6
Buttoud G, Place F, Gauthier M (2013) Advancing agroforestry on the policy agenda: a guide for decision-makers. Food and Agriculture Organization of the United Nations, Rome
Carsan S, Stroebel A, Dawson I, Kindt R, Swanepoel F, Jamnadass R (2013) Implications of shifts in coffee production on tree species richness, composition and structure on small farms around Mount Kenya. Biodivers Conserv 22(12):2919–2936
Carsan S, Stroebel A, Dawson I, Kindt R, Mbow C, Mowo J, Jamnadass R (2014) Can agroforestry option values improve the functioning of drivers of agricultural intensification in Africa? Curr Opin Environ Sustain 6:35–40
Cassman KG, Grassini P (2020) A global perspective on sustainable intensification research. Nat Sustain 3(4):262–268
Charles R, Munishi P, Nzunda E (2013) Agroforestry as adaptation strategy under climate change in Mwanga District, Kilimanjaro, Tanzania. Int J Environ Prot 3:29–38
Chavan SB, Newaj R, Rizvi RH, Ajit PR, Alam B, Handa AK, Dhyani SK, Jain A, Tripathi D (2021) Reduction of global warming potential vis-à-vis greenhouse gases through traditional agroforestry systems in Rajasthan, India. Environ Dev Sustain 23:4573–4593
Clough Y, Barkmann J, Juhrbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darras K, Putra DD, Erasmi S (2011) Combining high biodiversity with high yields in tropical agroforests. Proc Natl Acad Sci 108(20):8311–8316
Cook S, Silici L, Adolph B, Walker S (2015) Sustainable intensification revisited. International Institute for Environment and Development, London
Cowie AL, Orr BJ, Sanchez VC, Chasek P, Crossman ND, Erlewein A, Tengberg AE (2018) Land in balance: the scientific conceptual framework for land degradation neutrality. Environ Sci Policy 79:25–35
Dagar JC, Pandey CB, Chaturvedi CS (2014) Agroforestry: a way forward for sustaining fragile coastal and island agro-ecosystems. In: Agroforestry systems in India: livelihood security & ecosystem services, advances in agroforestry, vol 10. Springer, Berlin, pp 185–232
Dagar JC, Sileshi GW, Akinnifesi FK (2020) Agroforestry to enhance livelihood security in Africa: research trends and emerging challenges. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol vol 1. Springer Nature, Singapore, pp 71–134
Davis B, Di Giuseppe S, Zezza A (2017) Are African households (not) leaving agriculture? Patterns of households' income sources in rural sub-Saharan Africa. Food Policy 67:153–174. https://doi.org/10.1016/j.foodpol.2016.09.018
Dhakal A, Rai RK (2020) Who adopts agroforestry in a subsistence economy? Lessons from the Terai of Nepal. Forests 11(5):565
Dhyani S, Murthy IK, Kadaverugu R, Dasgupta R, Kumar M, Adesh Gadpayle K (2021) Agroforestry to achieve global climate adaptation and mitigation targets: are south Asian countries sufficiently prepared? Forests 12(3):303. https://doi.org/10.3390/f12030303

Duguma L, Nzyoka J, Minang P, Bernard F (2017) How agroforestry propels achievement of nationally determined contributions. ICRAF Policy Brief no. 34. World Agroforestry Centre, Nairobi, Kenya, p 8

Gaffney J, Bing J, Byrne PF, Cassman KG, Ciampitti I, Delmer D, Warner D (2019) Science-based intensive agriculture: sustainability, food security, and the role of technology. Glob Food Sec 23:236

Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Godfray HCJ (2013) Sustainable intensification in agriculture: premises and policies. Science 341(6141):33–34

Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A, Bayala J (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Secur 2:197–214

Geels FW, Kemp R (2007) Dynamics in socio-technical systems: typology of change processes and contrasting case studies. Technol Soc 29(4):441–455

Geiger K (2015) Characterizing the traditional tree-garden systems of Southwest Sri Lanka. Trop Resour 34:93–103

International Fund for Agricultural Development/United Nations Environment Programme (2013) Smallholders, food security and the environment. https://www.ifad.org/documents/10180/666cac24-14b6-43c2-876d-9c2d1f01d5dd

International Panel of Experts on Sustainable Food Systems (2016) From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. www.ipes-food.org

IPCC (2019) In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner HO, Roberts DC, Zhai P, Slade R, Connors S, Van Diemen R, Ferrat M (eds) Climate change and land: a special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, Geneva

IPCC (2021) Climate change: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, JBR M, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of Working Group I to the Sixth Assessment Report. Intergovernmental Panel on Climate Change, Geneva

Isbell F, Calcagno V, Hector A, Connolly J, Harpole WS, Reich PB, Loreau M (2011) High plant diversity is needed to maintain ecosystem services. Nature 477(7363):199–202

Khan N, Jhariya MK, Raj A, Banerjee A, Meena RS, Bargali SS, Kumawat A (2021) Agroforestry and its services for soil management and sustainability. In: Sustainable intensification for agroecosystem services and management, pp 353–377

Kiyani P, Andoh J, Lee Y, Lee DK (2017) Benefits and challenges of agroforestry adoption: a case of Musebeya sector, Nyamagabe District in southern province of Rwanda. For Sci Technol 13(4):174–180

Koohafkan P, Altieri MA, Gimenez EH (2012) Green agriculture: foundations for biodiverse, resilient and productive agricultural systems. Int J Agric Sustain 10(1):61–75

Kumar BM, Singh AK, Dhyani SK (2012) South Asian agroforestry: traditions, transformations, and prospects. In: Agroforestry—the future of global land use. Springer, Berlin, pp 359–389

Kuyah S, Öborn I, Jonsson M (2016) Trees in agricultural landscapes enhance provision of ecosystem services in sub-Saharan Africa. Ecosyst People 12:255–273. https://doi.org/10.1080/21513732.2016.1214178

Kuyah S, Öborn I, Jonsson M (2017) Regulating ecosystem services delivered in agroforestry systems. In: Dagar JC, Tewari VP (eds) Agroforestry: anecdotal to modern science. Springer, Berlin, pp 797–815

Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa a meta-analysis. Agron Sustain Dev 39(5):1–18

Kuyah S, Sileshi GW, Luedeling E, Akinnifesi FK, Whitney CW, Bayala J, Mafongoya PL (2020) Potential of agroforestry to enhance livelihood security in Africa. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes: recent advances and emerging challenges, vol 1. Springer Nature, Singapore, pp 135–167

Leakey R (2014) The role of trees in agroecology and sustainable agriculture in the tropics. Annu Rev Phytopathol 52:113–133

Leakey R (2017) Multifunctional agriculture: achieving sustainable development in Africa. Academic Press, San Diego, CA

Liu CLC, Kuchma O, Krutovsky KV (2018) Mixed-species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. Glob Ecol Conserv 15:e00419

Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333:616–620. https://doi.org/10.1126/science.1204531

Mahmud AA, Bhojiya AA, Raj A, Mk J (2021) Climate change adaptation and mitigation through a traditional agroforestry system. In: Advances in sustainable development and management of environmental and natural resources: economic outlook and opinions, vol 23, p 375

Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014a) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Sustain Challeng 6:8–14. https://doi.org/10.1016/j.cosust.2013.09.002

Mbow C, van Noordwijk M, Prabhu R, Simons T (2014b) Knowledge gaps and research needs concerning agroforestry's contribution to sustainable development goals in Africa. Curr Opin Environ Sustain 6:162–170

Mendelsohn R (2014) The impact of climate change on agriculture in Asia. J Integr Agric 13(4): 660–665

Miller DC, Muñoz-Mora JC, Christiaensen L (2017) Prevalence, economic contribution, and determinants of trees on farms across sub-Saharan Africa. Forest Policy Econ 84:47–61

Minang PA, Duguma LA, Bernard F, Mertz O, van Noordwijk M (2014) Prospects for agroforestry in REDD+ landscapes in Africa. Curr Opin Environ Sustain 6:78–82

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA (2012) Closing yield gaps through nutrient and water management. Nature 490(7419):254–257

Muschler RG (2016) Agroforestry: essential for sustainable and climate-smart land use. In: Tropical forestry handbook, 2nd edn. Springer, Berlin

Nicholls CI, Altieri MA, Vazquez L (2016) Agroecology: principles for the conversion and redesign of farming systems. J Ecosys Ecograph S5:010

Nzyoka J, Minang PA, Ogendi R, Duguma L (2018) The potential of agroforestry to enhance Land Degradation Neutrality. In: Nicklin S (ed) A better world: actions and commitments to the Sustainable Development Goals: life on land, vol 4. Leicester, Tudor Rose, pp 69–72

Orr A, Mwale B (2016) Adapting to adjustment: smallholder livelihood strategies in southern Malawi. World Dev 29:1325–1343

Ortiz-Bobea A, Ault TR, Carrillo CM, Chambers RG, Lobell DB (2021) Anthropogenic climate change has slowed global agricultural productivity growth. Nat Clim Chang 11(4):306–312

Pandey R, Aretano R, Gupta AK, Meena D, Kumar B, Alatalo JM (2017) Agroecology as a climate change adaptation strategy for smallholders of Tehri-Garhwal in the Indian Himalayan region. Small Scale For 16(1):53–63

Panel M (2013) Sustainable intensification: a new paradigm for African agriculture. Agriculture for Impact, London

Pingali P, Spielman D, Zaidi F (2016) Agricultural research in Africa: investing in future harvests. In: Lynam J, Beintema NM, Roseboom J, Badiane O (eds) Agricultural research in Africa: investing in future harvests, pp 139–170

Pradhan BB, Chaichaloempreecha A, Limmeechokchai B (2019) GHG mitigation in agriculture, forestry and other land use (AFOLU) sector in Thailand. Carbon Balance Manag 14(1):1–17

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114: 1571–1596

Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HCJ, Wratten S (2018) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1(8): 441–446

Rickards L, Howden SM (2012) Transformational adaptation: agriculture and climate change. Crop Pasture Sci 63(3):240–250

Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA (2017) Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag 16:145–163. https://doi.org/10.1016/j.crm.2017.02.001

Rosa-Schleich J, Loos J, Mußhoff O, Tscharntke T (2019) Ecological-economic trade-offs of diversified farming systems—a review. Ecol Econ 160:251–263

Rose DC, Sutherland WJ, Barnes AP, Borthwick F, Ffoulkes C, Hall C, Dicks LV (2019) Integrated farm management for sustainable agriculture: lessons for knowledge exchange and policy. Land Use Policy 81:834–842

Rosenstock TS, Dawson IK, Aynekulu E, Chomba S, Degrande A, Fornace K, Jamnadass R, Kimaro A, Kindt R, Lamanna C (2019) A planetary health perspective on agroforestry in sub-Saharan Africa. One Earth 1:330–344

Salvini G, Ligtenberg A, Van Paassen A, Bregt AK, Avitabile V, Herold M (2016) REDD+ and climate smart agriculture in landscapes: a case study in Vietnam using companion modelling. J Environ Manage 172:58–70

Sharma N, Bohra B, Pragya N, Ciannella R, Dobie P, Lehmann S (2016) Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. Food Energy Secur 5:165–183

Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad Dev 29(11):3886–3897

Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11(4):368

Shrestha BM, Chang SX, Bork EW, Carlyle CN (2018) Enrichment planting and soil amendments enhance carbon sequestration and reduce greenhouse gas emissions in agroforestry systems: a review. Forests 9(6):369

Sood KK, Mitchell CP (2009) Identifying important biophysical and social determinants of on-farm tree growing in subsistence-based traditional agroforestry systems. Agr Syst 75(2):175–187

Tittonell P, Klerkx L, Baudron F, Félix GF, Ruggia A, van Apeldoorn D, Rossing WA (2016) Ecological intensification: local innovation to address global challenges. In: Sustainable agriculture reviews, pp 1–34

UNCCCD (2016) Land in balance. http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/10_2016_spi_pb_multipage_eng.pdf

Van Noordwijk M (2020) Agroforestry as nexus of sustainable development goals. Iop Conf Ser Earth Environ Sci 449:012001

van Noordwijk M, Tata HL, Xu J, Dewi S, Minang PA (2012) Segregate or integrate for multifunctionality and sustained change through rubber-based agroforestry in Indonesia and China. In: Agroforestry-the future of global land use. Springer, Berlin, pp 69–104

Van Noordwijk M, Duguma LA, Dewi S, Leimona B, Catacutan DC, Lusiana B, Prabhu R (2019) Agroforestry into its fifth decade: local responses to global challenges and goals in the Anthropocene. In: Sustainable development through trees on farms: agroforestry in its fifth decade, pp 397–418

Van Noordwijk M, Ekadinata A, Leimona B, Catacutan D, Martini E, Tata HL, Öborn I, Hairiah K, Wangpakapattanawong P, Mulia R, Dewi S, Rahayu S, Zulkarnain T (2020) Agroforestry options for degraded landscapes in Southeast Asia. In: Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded landscapes—recent advances and emerging challenges, vol vol 1. Springer Nature, Singapore. https://doi.org/10.1007/978-981-15-4136-0_11

van Noordwijk M, Coe R, Sinclair FL, Luedeling E, Bayala J, Muthuri CW, Minang PA (2021) Climate change adaptation in and through agroforestry: four decades of research. Mitig Adapt Strat Glob Chang 26(5):1–33

Waldron A, Garrity D, Malhi Y, Girardin C, Miller DC, Seddon N (2017) Agroforestry can enhance food security while meeting other sustainable development goals. Trop Conserv Sci 10: 1940082917720667

Zerihun MF (2021) Agroforestry practices in livelihood improvement in the eastern cape province of South Africa. Sustainability 13(15):8477

Zomer RJ, Trabucco A, Coe R, Place F (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. In: ICRAF Working Paper-World Agroforestry Centre, Nairobi, Kenya (89)

Zomer RJ, Trabucco A, Coe R, Place F, van Noordwijk M, Xu JC (2014) Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. In: ICRAF working papers. Working Paper 179, World Agroforestry Centre (ICRAF) Southeast Asia Regional Program (ed WACISARPD WP14064. PDF). (pp 33–33). Bogor, Indonesia

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, Mortimer PE (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6:29987

Chapter 21
A Framework for Analysing Spatial Patterns and Extent of Influence by Single Trees on Ecosystem Properties in Agroforestry

Gudeta Weldesemayat Sileshi and Arun Jyoti Nath

Abstract Scattered and isolated trees are a common feature of traditional agroforestry systems, urban landscapes and many other natural and human-modified landscapes. However, they are rarely systematically studied, and our understanding of their influence on ecosystem properties is incomplete. The challenge is to provide accurate information on their influences in the landscapes they occur so that evidence-based policies and practices can be formulated for their preservation and management. We undertook a review and analyses with the aim to provide evidence and mechanistic explanation for spatial patterning of ecosystem properties around isolated trees. Using 36 datasets collected from sites across the globe, we show that single-tree effects are monotonically decreasing functions of distance from the trunk. Lateral root density, hydraulic conductivity, soil organic carbon concentrations, nutrient pools, crop yields and biomass of understory vegetation showed predictable spatial patterns consistent with distance-decay models implicit in Tobler's first law of geography and the neutral theory of biogeography. In 24 out of the 36 cases analysed, the power-law distance-decay model described the patterns better than the exponential decay model. It is concluded that tree effects exceed the crown projection area, and therefore, the contribution of isolated tree stands to ecosystem functioning may be disproportionately larger than the area they occupy. The analyses provided a new perspective of pattern formation supporting the notion that isolated trees are keystone structures in the ecosystems where they occur. This provides justification for their protection and prudent management. The patterns elucidated also provide a theoretical justification for a paradigm shift in study design and statistical analysis of tree effects in agroforestry. Since measurements are monotonically decreasing (or increasing) functions of distance from the trunk, we

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discourage the use of distance as a fixed effect in statistical models when analysing data from agroforestry systems.

Keywords Anisotropy · Distance-decay · Dehesa · Montado · Influence circles · Keystone structure · Oligotrophic

21.1 Introduction

Scattered and isolated trees are a common feature of traditional agroforestry systems and many natural, cultural and human-modified landscapes worldwide (Hall and Bunce 2011; Lindenmayer et al. 2012; Manning et al. 2006). Typical examples include dehesas and montados in Mediterranean landscapes (Joffre et al. 1999), savannas and parklands in Africa (Boffa 1999) and India (Batish et al. 2008), Cerrados and Caatinga in Brazil, Trachypogon savannas in Venezuelan, paddocks in the arid rangelands of Australia (Wilson and Lemon 2004), oak savannas in North America, British wood-pastures and the forest-tundra transition zone (Manning et al. 2006). Isolated trees are also a common feature of urban landscapes (Streiling and Matzarakis 2003). Although the role of isolated trees in bio-geochemical processes and biodiversity has recurrently attracted significant researcher attention, they are often poorly managed because their contributions remain underappreciated. Populations of large old trees are also rapidly declining in many parts of the world (Lindenmayer et al. 2012) due to urbanization, infrastructure development, agricultural activities and grazing (Lindenmayer et al. 2014; Miguel et al. 2013; Stagoll et al. 2012). The decline in old trees will have serious implications for ecosystem integrity and biodiversity (Lindenmayer et al. 2014).

Isolated trees play many ecological roles including the storage of large amounts of carbon, nutrient cycling, improved crop and pasture productivity (Abdallah et al. 2012; Miguel et al. 2013; Vetaas 1992), provision of key habitats for wildlife (Dean et al. 1999; Lindenmayer et al. 2014) and improvement of the urban climate (Streiling and Matzarakis 2003). In systems where scattered trees are associated with crops or pasture, the trees play a vital role not only in crop and forage production, but also soil and water conservation and CO_2 sequestration (Gebrewahid et al. 2018; Nath et al. 2021; Roupsard et al. 2020; Sileshi 2016). For example, the trees create long-term spatial heterogeneity in resources of high interest for adaptation and mitigation of climate change, and the provision of ecosystem services especially in dry areas (Roupsard et al. 2020; Sileshi 2016; Tzuk et al. 2020). At the landscape scale, their roles may include increased tree cover, habitat connectivity for animals, genetic connectivity for tree populations, and ecological continuity through time (Manning et al. 2006). At the local scale, their ecological functions may include modification of the hydrology (Chandler and Chappell 2008), provision of a distinct microclimate, increased soil fertility, plant species richness and structural complexity (Lindenmayer et al. 2012; Miguel et al. 2013; Manning et al. 2006; Oliver et al. 2006). Soil enrichment by trees has been reported to create islands of fertility even in oligotrophic soils, thus supporting distinctive plant assemblages and hotspots of animal activity (Belsky et al. 1989; Dean et al. 1999; Rhoades 1997; Schnabel et al. 2013; Sileshi 2016). Even in arid areas, isolated trees have been shown to increase biodiversity by structuring the habitat vertically and horizontally (Dean et al. 1999). However, contradictory reports are common, where some studies reported increased soil fertility and understory vegetation biomass, while others reported decrease or no effects (e.g. Abrams et al. 1997; Austin-Petersen et al. 2002; Sileshi 2016).

These conflicting results could arise either from context-specific interactions, differences in tree species traits and the environment (Ayres et al. 2009). Figure 21.1 provides a simple conceptual diagram of the possible interactions between the environment, the tree, and understory vegetation. The growth and performance of a particular tree species largely depends on climate and soil properties, but tree spacing, density, age and tree management (e.g. pruning, lopping, etc.) can also play a determining role on the size of their zones of influence. The leaf lifespan (evergreen vs. deciduous) plays a role in controlling the timing of the litter fall, while litter stoichiometry may control the litter decay rates. These and the distribution of fine roots and their phenology together with soil water content, temperature, soil biota may control accumulation of soil organic matter (SOM), nutrient pools, and finally the productivity of understory vegetation (Fig. 21.1).

Since tree species exhibit broad variation in their canopy and root architecture, and the quality and quantity of their inputs to soil, it is likely that these differences will create distinctive soil environments (Ayres et al. 2009). However, most of these effects show broadly similar spatial patterns centred around each tree (Amiotti et al. 2000; Jose and Gillespie 1998; Zinke 1962). These patterns, called 'influence circles' (Fig. 21.1), have been widely demonstrated by empirical data (Amiotti et al. 2000; Zinke 1962). The younger and closer the trees are, the more their influence circles merge; but a more definite pattern will emerge as the trees grow older and the spacing becomes wider (Zinke 1962). Despite the complex interactions between trees and their growing environment (Fig. 21.1), certain features remain consistent as they follow first principles. The distance-decay of spatial interactions is one such principles. Distance-decay principles posit that the nearer two locations are, the greater is the expected interaction between the two. This has been formalized as Tobler's first law of geography (Tobler 1970) and the neutral theory of biogeography and community assembly (Hubbell 2001; O'Dwyer et al. 2009; O'Dwyer and Green 2010).

Distance plays a cardinal role in interactions of various types underpinning a host of empirical regularities (Chen 2015; Hubbell 2001; O'Dwyer et al. 2009; Tobler 1970). For example, the similarity among pairs of biological communities typically decays with increasing spatial or environmental distance (Nekola and White 1999). Similarly, tree root profiles often follow a negative exponential pattern of decay (Jackson et al. 1996). Tree root densities and soil fertility also show a sharp decrease with distance from the trunk (e.g. Moreno and Obrador 2007; Moreno et al. 2005; Sileshi 2016). Nevertheless, our knowledge of distance-decay in single-tree effects on soil and understory crops is limited. A key challenge for good management (i.e. in managed systems) is to understand the spatial patterning in soil functions and crop

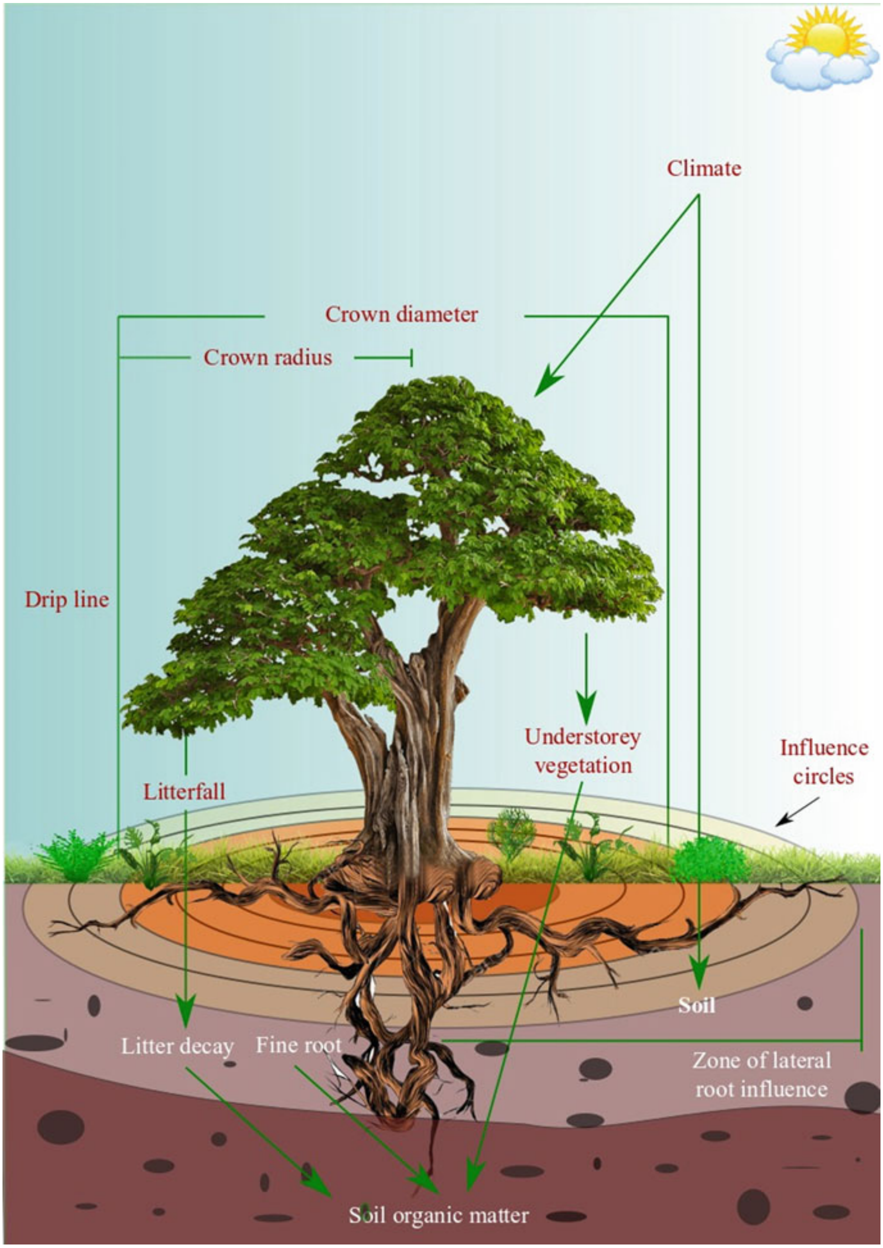

Fig. 21.1 Conceptual representation of the interactions between the environment, single trees and understory vegetation with a schematic representation of the ecological field showing zones of tree crown (canopy) and root influence. The elliptical circles represent influence circles

productivity around isolated trees. This kind of information is relevant for land owners and natural resource managers to enable them to take more informed decisions on whether or not to retain isolated trees in the landscape. The challenge for ecologists lies in accurately modelling and quantifying the impacts of isolated trees so that this information can be quantitatively scaled up to whole farm and landscape levels. In many studies in the past, inferences were based on study designs where distance classes are used as fixed effects. This kind of analysis assumes that measured variables are identically and independently distributed among distance classes, while in reality this is not true. Although distance-decay models can reveal spatial patterns and provide mechanistic insights, they have not been used in modelling effects of isolated trees in managed ecosystems. Therefore, the objective of this paper was to model and provide mechanistic insights into the spatial patterning of single-tree influences in the ecosystems where they occur. The key hypotheses were: (1) single-tree effects are monotonically decreasing functions of distance from the trunk consistent with distance-decay models of spatial interaction, and (2) the power-law distance-decay model describes single-tree effects better than the exponential distance-decay model.

21.2 Methods and Analytical Framework

21.2.1 Sources of Data

We searched the literature focussing on published primary literature and reviews, and identified studies that reported measurements of response variables at a minimum of five distance classes (i.e. sample size $N \geq 5$) from the tree trunk in the target systems. This minimum was set because model parameters and the Akaike information criterion (AIC) used for model comparison cannot be correctly estimated for $N < 5$. In total, 36 datasets from 15 peer-reviewed publications qualified for inclusion. The methods used for data collection in those studies are briefly described below organized according to the number of studies and geographic area. A larger number of studies were found in Mediterranean and Europe landscapes and Africa followed by Asia. One study each was found in Australia and the Americas (Table 21.1).

21.2.1.1 Parklands in the Mediterranean and Europe

In Mediterranean landscapes, Dehesa (in Spain) and montado (in Portugal) are high nature and cultural value systems forming one of the largest agroforestry land-uses in Europe (den Herder et al. 2017; Moreno et al. 2018; Pinto-Correia et al. 2018). Dehes is dominated by Mediterranean tree species that are distributed without a regular pattern on pasture land, cropland or fallow land (Joffre et al. 1999; Simón et al. 2012). The trees are originally derived from oak (*Quercus* spp.) forests which

Table 21.1 Studies that qualified for inclusion in this analysis

Source	Variable analysed	Location
Chandler and Chappell (2008)	Hydraulic conductivity under *Quercus robur*	Lancashire, England
Gea-Izquierdo et al. (2010)	Grass yield, soil organic carbon (SOC) and total nitrogen (N) under *Quercus ilex*	West Central Spain
Moreno and Obrador (2007)	Total N under *Quercus ilex*	Central West Spain
Montero et al. (2008)	Solar radiation under *Quercus ilex*	Southwest Spain
Alemie (2009)	Light intensity, soil hydrophobicity; maize yield under *eucalyptus*	Northern Ethiopia
Grouzis and Akpo (1997)	Herbaceous vegetation biomass under *Balanites* and *acacia*	Ferlo zone, Senegal
Weltzin and Coughenour (1990)	Grass biomass under *Acacia tortilis*	Turkana, Kenya
Tomlinson et al. (1998)	Root number, total N, available phosphorus (P) and potassium (K) under *Parkia biglobosa*	Burkina Faso
Belsky et al. (1989)	SOC, available P, Ca, K, pH, soil moisture and temperature under *Acacia tortilis* and *Adansonia digitata*	Tsavo, Kenya
Hailu et al. (2000)	Litter biomass, SOC and soil nutrients under *Millettia ferruginea*	Wondogenet, Ethiopia
Yadav et al. (1993)	Mustard yield under *Acacia nilotica*	Haryana, India
Singh et al. (1998)	Wheat yield under *Populus deltoides*	Punjab, India
Singh and Kohli (1992)	Phytotoxins in the soil, yield of chickpea, lentil, wheat, cauliflower, toria under *Eucalyptus*	India
Oliver et al. (2006)	Litter biomass, soil SOC and N under *Eucalyptus nova-anglica*	New South Wales, Australia
Schnabel et al. (2013)	SOC and N under *Quercus douglasii*	Northern California, USA

were progressively thinned, through time creating an open park-like savannah (Moreno et al. 2013; Simón et al. 2012). The tree species in dehesa can be either evergreen species mainly holm oak (*Quercus ilex*) and cork oak (*Q. suber*) or deciduous species such as Pyrenean oak (*Q. pyrenaica*) and (c) semi-deciduous species such as Lusitanian oak (*Q. faginea*) and Algerian oak (*Q. canariensis*) (Moreno et al. 2013). Montado is mainly characterized by pure or mixed stands of cork oak, holm oak and Pyrenean oak (Pinto-Correia and Mascarenhas 1999). The trees occur at a density of 15–45 per hectare with a canopy cover of 21–40% (Moreno and Pulido 2009).

From Mediterranean and Europe, studies by Chandler and Chappell (2008), Gea-Izquierdo et al. (2010), Moreno and Obrador (2007) and Montero et al. (2008) qualified for inclusion in this analysis. Chandler and Chappell (2008) studied the influence of English oaks (*Quercus robur*) trees on saturated hydraulic conductivity (K_s) within the 0.10 to 0.25 m soil depth in parklands in Lancashire, England. K_s was measured at seven distances (1, 3, 5, 7, 9, 11 and 13 m) from the trunk along eight transects. In this analysis, the geometric mean and median K_s (m $s^{-1} \times 10^{-6}$) data recorded at each distance from the tree were used for modelling. In the study by Gea-Izquierdo et al. (2010), variations in grass yield, soil organic matter (SOM %) and total nitrogen (N %) were quantified under holm oak trees in West Central Spain. For sampling grass, eight points were placed proportionally to the crown radius (R) in North-East (NE) direction representing the lowest exposure to sunlight, and eight in the South-West (SW) representing the highest exposure. The sampling points for grass yield were located at six distances (0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0 × R) from each tree in NE and SW directions. Then, herbaceous material was collected in May and April using 50 × 50 cm frames, and dried for 48 h at 60 °C. Similarly, soil samples were collected from the top 20 cm depth at 6 distances proportional to the crown radius (0.375, 0.75, 1.0, 1.5, 2.0 and 2.5 × R) in the NE and SW orientations. In the study by Moreno and Obrador (2007), soil nutrients contents were analysed in four Spanish dehesas under three land use types: isolated holm oak with an understory of native grasses, shrub encroached and crops. Six oak trees were selected randomly per land use, and soil samples were collected at five distances from each tree trunk (i.e. 2, 5, 10, 15 and 20 m) from the 0 to 30 cm soil depth. Total soil nitrogen (%) contents under the three land use types (i.e. native grasses, shrub encroached and crops) were analysed separately for the present review. In the study by Montero et al. (2008), the radiation transmitted through holm oak tree canopy (radius 3.9 to 4.4 m) to the understory pasture and crops was quantified in dehesas of Southwest Spain. The percentage of radiation transmitted was recorded at six distances from the tree trunk (0.5, 1, 5, 10, 20 and 30 m).

21.2.1.2 Savannas and Agroforestry Parklands in Africa

Savannas are a vegetation type with a continuous grass layer interspersed with a discontinuous layer of trees, shrubs and forbs (Siebert and Dreber 2019). Small-scale facilitative interaction between the woody and herbaceous components and competitive interaction on larger scales together explain the dynamic coexistence of trees and herbaceous vegetation (Vetaas 1992). Isolated trees are known to structure plant and animal communities and determine patterns and patch dynamics in arid and semi-arid savannas (Belsky et al. 1989; Dean et al. 1999). Most African savannas are a mosaic of savanna habitats and small-scale agriculture (Tripathi et al. 2021). Many African savannas are the new frontier of agricultural expansion (Estes et al. 2016; Tripathi et al. 2021).

Agroforestry parklands are one of the most widespread traditional land use systems in African savannas (Boffa 1999; Teklehaimanot 2004). They represent traditional land use systems in the semi-arid or subhumid tropics in West Africa, Central Africa, East Africa and to a lesser extent in southern Africa (Boffa 1999). Farmers usually protect naturally regenerating savanna trees during tillage operations thus keeping tree density low so that canopy cover is not continuous. Therefore, isolated tree stands of uneven age, height, and canopy are found associated with crops. Although parklands are highly variable, the common species include *Faidherbia albida*, *Parkia biglobosa*, *Vitellaria paradoxa*, *Adansonia digitata, Balanites aegyptiaca, Tamarindus indica* and *Vachelia* (formerly *Acacia*) species (Boffa 1999; Teklehaimanot 2004).

Six studies from African savannas and agroforestry qualified for inclusion in the analysis. These are studies by Grouzis and Akpo (1997), Weltzin and Coughenour (1990), Tomlinson et al. (1998), Belsky et al. (1989), Alemie (2009) and Hailu et al. (2000). In the study by Grouzis and Akpo (1997), variations in herbaceous vegetation with distance from *Balanites* and *Acacia* trees were determined in a dry Sahelian savanna in Senegal. The understory vegetation was harvested from 50 × 50 cm plots at distances of 1.25, 2.5, 3.75, 5.0, 6.25, 7.5, 8.75 and 10 m from the trunks in the four cardinal directions. Biomass samples were dried to a constant weight at 85 °C.

In Weltzin and Coughenour (1990) grass biomass under 15 isolated *Acacia tortilis* trees was quantified in a savanna in Turkana in Kenya. Grass was harvested from 50 × 50 cm plots placed at nine distances (bole, 25%, 50%, 75%, 100%, 125%, 150%, 175% and 200% of the canopy radius) along each transect, where 100% of the canopy radius represented the drip line. Grassy vegetation was clipped to ground level and dried to constant weight at 85 °C.

Tomlinson et al. (1998) determined the root systems of mature *Parkia biglobosa* trees (age 40–60 years, mean diameter at breast height of 49.5 cm and crown radius of 7.02 m) on three savanna locations in Burkina Faso. Roots were excavated using a logarithmic spiral trench to a depth of 60 cm, and the numbers of roots were recorded by placing 50 × 50 cm quadrats positioned along the spiral trench up to a distance of 10 m from the trunk with increments of 1 m. Root counts were expressed as number of roots m^{-2}. Soil samples were taken at distances of 1, 3, 5, 7 and 9 m measured linearly from the trunk, and total nitrogen, available phosphorus and available potassium were determined.

Belsky et al. (1989) quantified vegetation and soil characteristics around isolated, mature trees of *Acacia tortilis* and *Adansonia digitata* in Tsavo National Park, a semi-arid savanna in Kenya. Soil samples were collected at 5 m intervals along the 50-m vegetation transects from the 0 to 10 cm depths and SOM, P, Ca, K and soil pH were determined. In addition, soil temperatures were recorded in the 5 and 10 cm depth at 5-m intervals along 40-m transects extending east and west from the bases of target trees. In this analysis, SOM and soil temperatures recorded at 5 cm depth (mean of the east and west transects) were analysed. Since P, Ca and K concentrations followed the same pattern as SOC, these were not presented to avoid cluttering.

Alemie (2009) determined the effect of *Eucalyptus* trees in agroforestry on light intensity, soil hydrophobicity and maize yields at different distances in northern Ethiopia. Light intensity was determined using a light meter at 0.5, 1, 2, 5, 10, 15, 20 and 40 m distances from the tree in maize fields at different times during a day. For this analysis data collected in the morning (9:00 a.m.) and at noon (12:00) were used. Hydrophobicity was determined using the water drop penetration time (WDPT) test. This test determines how long water repellence persists on the soil surface. The test was done on soil samples collected at 16 distances from the tree (0–300 cm) at 20 cm intervals from three separate plots. The time it took (in seconds) for complete penetration of water drops was recorded. For this analysis, the mean of the data from field dry soil was used. Maize grain yield was recorded in 2 m $\times$ 2 m plots at 1, 5, 10, 15, 20 and 40 m distances from the tree trunk, and values were converted to a hectare (kg ha^{-1}). For this analysis, the response ratio was calculated (see below for details) from the mean of three replicate plots.

Hailu et al. (2000) quantified variations in litter biomass, SOC and soil nutrients under *Millettia ferruginea,* a nitrogen fixing tree maintained by farmers in traditional agroforestry practices in southern Ethiopia. The crown diameter of the trees was on average 6.75 m. Sampling plots of 0.5 $\times$ 0.5 m were established around four isolated trees in each of four radial transects at distances of 0.75, 2.75, 4.75, 6.75 and 29.5 m from the tree, and litter biomass, SOC, total N, available P, Mg, Na and CEC were determined.

21.2.1.3 Agroforestry Practices in India

Isolated trees are also common elements of various agroforestry practices in India especially in the agrisilvicultural, agrosilvopastoral and silvopastoral systems, covering an estimated area of 8.7, 5.6 and 2.4 million ha (Nath et al. 2021). These are described in detail in Nath et al. (2021). Three studies namely, Yadav et al. (1993), Singh et al. (1998) and Singh and Kohli (1992) qualified for inclusion in this analysis. In the study by Yadav et al. (1993), yields of mustard were measured under *Acacia nilotica* on sample plots of one m^2 laid out in concentric circles around each tree at nine distances (1, 3, 5, 7, 9, 11, 14, 18 and 22 m) from the tree. In the study by Singh et al. (1998), wheat yields were measured at 11 distances up to 20 m from *Populus deltoides* in the Punjab region of India. Singh and Kohli (1992) recorded phytotoxins in the soil at distances of 0.5, 1, 2, 3, 5 and 10 m under *Eucalyptus tereticornis*. They also recorded the economic yield of chickpea (*Cicer arietinum*), lentil (*Lens esculentum*), wheat (*Triticum aestivum*), cauliflower (*Brassica oleracea*), toria (*Brassica campestris*) at distances of 1, 2, 3, 5, 7, 9, 11, 12, 13 and 15 m from *Eucalyptus* shelterbelts.

21.2.1.4 Paddock Trees in Australia

Across much of temperate Australia, isolated trees or small patches of trees locally called paddock trees are a visually defining feature of the agricultural landscape, where they occupy as much as 20 million hectares of farmland (Eldridge and Wong 2005; Wilson and Lemon 2004). These are particularly common in the arid rangelands, where remnant patches of native vegetation and isolated trees of *Eucalyptus* species form an open canopy within a matrix of improved pasture (Eldridge and Wong 2005). A study by Oliver et al. (2006) qualified for inclusion in this analysis. In that study, litter biomass as well as soil SOC and N was quantified under

Eucalyptus nova-anglica in open paddocks in New South Wales. Sampling took place in a star design at 16 distances from the tree every second metre along 30-m transects. Total litter (leaves, twigs, etc.) was collected in a 25 × 25 cm quadrat at each sampling point and air-dried at room temperature for 1 week before weighing. At the same points, soil samples were taken from the 0 to 10 cm depth to determine SOC (%) and soil nitrogen (%).

21.2.1.5 Oak Savannas of North America

Oak savannas of North Americas are characterized by an overstory dominated by oak species with 10–30% crown cover (Dey et al. 2017). Like the Spanish dehesas, oak savannas are formed of evergreen and deciduous oaks within a grassland matrix dominated by annual grasses and forbs, where livestock production is integrated (Moreno et al. 2013). The common oaks are evergreen species including coast live oak (*Quercus agrifolia*) and interior live oak (*Q. wislizeni*), deciduous species mainly blue oak (*Q. douglasii*) and valley oak (*Q. lobata*), and semi-deciduous species Engelmann oak (*Q. engelmannii*) (Moreno et al. 2013). One study by Schnabel et al. (2013) from this system qualified for inclusion in this analysis. The authors measured SOC (%) and N (%) at 11 equal distances from the tree bole using canopy radius (*R*) increments of 0.25 (0–2.5 × *R*) in grazed soils in the Sierra Nevada foothills of northern California. Samples were taken around four blue oak (*Q. douglasii*) trees along the 11 sampling points established in the four directions (i.e. north, east, south and west transects). For each sampling distance, the mean of 16 measurements (4 trees × 4 directions) was used for analysis.

21.2.2 Theory, Models and Data Analyses

The various factors depicted in Fig. 21.1 may influence parameters of the distance-decay models. However, for a given tree in a specific location, these factors are constant, and therefore, the distance-decay modelling can be performed without further complications. The modelling in the present analysis is based on existing theory, namely, Tobler's first law (Tobler 1970) and the neutral theory of biogeography and community assembly (Hubbell 2001; O'Dwyer et al. 2009). Tobler's first law of geography states that everything is related to everything else, but near things are more related than distant things. In his Neutral Theory, Hubbell (2001) proposed the distance-decay of similarity in community composition under ecological drift. Indeed, neutral theory provides a null model for ecologists concerned with the question of how community similarity changes with distance across a landscape (Nekola and White 1999). Distance-decay models are sensitive to key spatial processes and therefore serve as a powerful tool for testing mechanistic ecological theories (Morlon et al. 2008). However, the choice of the functional form can make important difference for predictions.

Distance-decay patterns are normally modelled using the power-law distance-decay model (PDM) and exponential distance-decay model (EDM) (Nekola and White 1999; O'Dwyer et al. 2009; Sileshi and Arshad 2012). However, the performances of the PDM and EDM differ with observational scale (Nekola and McGill 2014). According to a meta-analysis of 26 ecological and four human-system datasets (Nekola and McGill 2014), PDM prevailed at small scale where the species pool remains constant, but EDM prevailed at larger scales over which the species pool varies. The difference between PDM and EDM is significant due to the distributional assumptions inherent in the mathematical functions involved.

The exponential function describes a simple distribution (Chen 2015), whereas the power function describes a scale neutral and complex distribution. As such the power-law function has been widely used in the studies of complexity in physical and biological phenomena (Chen 2015; Marković and Gros 2014). The origin of the power-law behaviour in complex systems is the property of self-organized criticality (Bak et al. 1987; Marković and Gros 2014). According to Chen (2015) a power-law distribution can be deduced from a pair of exponential distributions. This suggests that a power law is based on dual entropy-maximizing processes, which are of unity of opposites in self-organized evolution (Chen 2015). When placed in a spatial context, PDM implies that the strength of relationships between locations decreases as a function of distance at all spatial scales (Palmer 2005).

In this analysis, we applied both the PDM and EDM assuming two scenarios: Scenario 1 represents situations where the tree depresses a measured variable close to the trunk (Fig. 21.2a), whereas Scenario 2 represents the tree elevates the measured variable near the trunk due to some positive (facilitative) effects (Fig. 21.2b). In either case, the tree effects are hypothesized to be monotonically decreasing functions of distance from the trunk.

In an unconstrained system, EDM has the following form:

$$Y = \alpha e^{-\beta D} \tag{21.1}$$

where Y is the dependent variable, D is distance from the origin (here the tree base), e is the base of the natural logarithm, α represents an initial value of Y and β is the exponent.

The PDM has the following form:

$$Y = \alpha D^{-\beta} \tag{21.2}$$

where α is the normalization constant and β is the exponent often treated as a scale-invariant quantity. In both Eqs. (21.1) and (21.2), β represents the rate of decay, i.e., the proportion of similarity lost per unit distance.

In EDM and PDM, β is of great interest because it is key for interpreting scaling relationships, and addressing hypotheses about interactions at different scales. Estimates of β often tend to be scale invariant and therefore may not significantly differ from each other for a given relationship studied in different circumstances

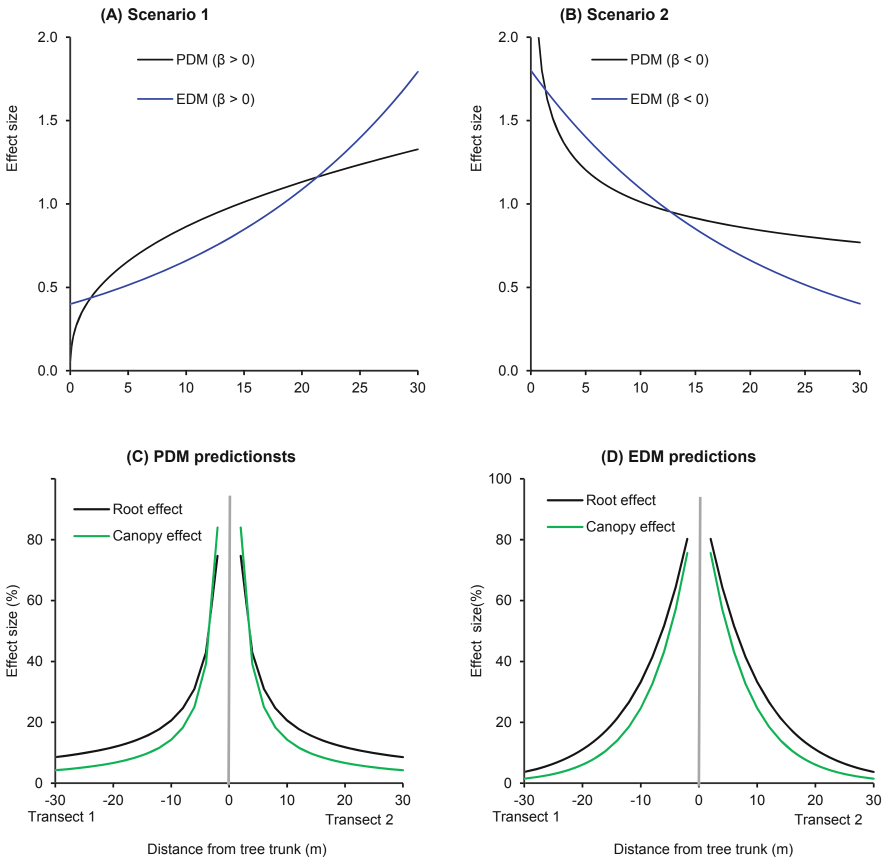

Fig. 21.2 Conceptual representation of tree effects assuming Scenario 1 (**a**) and Scenario 2 (**b**), and hypothesized scenarios of distance-decay in canopy and root effects assuming power-law (**c**) and exponential (**d**) distance-decay. The tree is located at distance 0, and its canopy effect is assumed to decay faster than the root effect beyond the drip line

(Tables 21.1, 21.2 and 21.3). If the base of the tree is taken as an invariant point source (i.e. $\alpha = 100\%$ tree effect) for a hypothetical pattern, Y is expected to vary as in Fig. 21.2c, d in the different directions away from the tree. In that sense, Y may be conceptualized as an interaction strength varying from 0 for no tree influence in the open area to 100 for maximum effect near the trunk. β will be significantly larger than 0 if the tree depresses the measured variable near the trunk with greater intensity, but the tree effect decays with distance (Fig. 21.2a). Conversely, β will be significantly smaller than 0 if the tree effect is positive or facilitative and the values of the variable are elevated near the trunk relative to locations further away (Fig. 21.2b).

The tree effect can be partitioned into aboveground (canopy) and belowground (root) effects, which decay with distance as demonstrated by Barbier et al. (2008)

Table 21.2 Distance-decay of measured variables assuming Scenario 1 (the variable is depressed closer to tree trunks) and estimates of the exponents (β) and Akaike information criterion

Variable	Data source	β (95% CL)[a]		AIC_c	
		PDM	EDM	PDM	EDM
Light transmitted	Alemie	0.60 (0.18; 1.01)	0.03 (0.01; 0.06)	**−7.2**	−0.4
Light intensity	Montero	0.26 (0.14; 0.38)	0.02 (0.01; 0.05)	**41.5**	51.7
Soil temperature 12 h	Belsky	0.04 (0.01; 0.07)	0.007 (0.002; 0.011)	**20.0**	20.2
Soil temperature 15 h	Belsky	0.03 (0.02; 0.05)	0.005 (0.001; 0.009)	**13.8**	20.5
Mustard yield	Yadav et al.	0.39 (0.16; 0.62)	0.04 (0.01; 0.08)	**−24.1**	−16.1
Maize yield	Alemie	0.60 (0.18; 1.01)	0.03 (0.01; 0.06)	**−7.2**	−0.4
Wheat yield	Singh and Kohli	0.83 (0.54; 1.11)	0.08 (0.03; 0.12)	**−39.6**	−25.9
Chickpea yield	Singh et al.	0.82 (0.33; 1.30)	0.10 (0.02; 0.17)	**−23.7**	−16.9
Lentil yield		1.15 (0.81; 1.49)	0.13 (0.07; 0.19)	**−36.4**	−24.8
Toria yield		1.07 (0.45; 1.69)	0.12 (0.03; 0.20)	**−23.3**	−16.9
Cauliflower yield		1.41 (0.87; 1.95)	0.14 (0.07; 0.22)	**−31.6**	−23.7
Available P	Alemie	0.63 (0.13; 1.14)	0.03 (0.02; 0.04)	10.1	**−3.5**
Exchangeable ca		0.10 (0.03; 0.18)	0.01 (−0.01; 0.02)	**12.1**	19.7

[a]Figures in parentheses are 95% confidence limits of β. All β estimators were unbiased ($|g| < 1.0$) except for PDM in chickpea and toria yields where skewness was apparent

and Belsky et al. (1989). Figure 21.2c, d depicts scenarios for canopy and root effects assuming PDM and EDM. Predictions of EDM (Fig. 21.2c) decay faster rate than PDM (Fig. 21.2d). The root effect is hypothesized to decay at a much slower rate than canopy effects (Fig. 21.2c, d) because lateral roots can extend several meters beyond the crown projection area (Barbier et al. 2008; Belsky et al. 1989), and much of the competition among plants takes place belowground. For simplicity, Fig. 21.2c, d depicts isotropy in measured variables, i.e., identical properties with values of β being the same in all transects. However, our default model assumes anisotropy (directional variations in β) along different transects. This is because Y may vary with cardinal directions, slope or aspect arising from differences in light and rainfall interception or surface run off. Normally, roots show symmetrical lateral distribution when trees grow on plane soil, but asymmetry is common on steep slopes as a consequence of preferential root elongation to increase the plant's stability (Chiatante et al. 2002).

Table 21.3 Distance-decay of variables assuming Scenario 2 (the variable is elevated closer to tree trunks) and estimates of the exponents (β) and Akaike information

Variable	Data source	β (95% CL)[a]		AIC_c	
		PDM	EDM	PDM	EDM
Lateral root	Tomlinson	−0.48 (−0.53; −0.44)	−0.14 (−0.18; −0.10)	**53.1**	72.69
Conductivity	Chandler and Chappell	−0.35 (−0.53; −0.17)	−0.08 (−0.11; −0.05)	−1.5	**−9.5**
Hydrophobicity	Alemie	−0.13 (−0.21; −0.04)	−0.02 (−0.018; −0.009)	223.5	**193.4**
Phytotoxins	Singh and Kohli	−0.14 (−0.46; 0.18)	−0.07 (−0.017; 0.022)	70.5	**67.0**
Grass yield	Gea-Izquierdo (May)	−0.26 (−0.38; −0.14)	−0.07 (−0.09; −0.05)	−18.6	**−23.8**
	Gea-Izquierdo (April)	−0.48 (−0.64; −0.32)	−0.14 (−0.18; −0.10)	−29.6	**−32.9**
	Weltzin	−0.14 (−0.23; −0.05)	−0.01 (−0.01; −0.005)	75.0	**54.4**
Phytomass	Grouzis	−0.43 (−0.49; −0.37)	−0.11 (−0.15; −0.06)	**21.9**	38.40
Herb. Litter	Oliver	−0.31 (−0.60; −0.02)	−0.06 (−0.10; −0.03)	11.7	**0.3**
Total litter	Oliver	−0.60 (−0.83; −0.37)	−0.14 (−0.17; −0.11)	48.4	**26.1**
Tree litter	Hailu	−0.44 (−0.95; −0.06)	−0.18 (−0.33; −0.03)	75.9	**70.6**
SOC (%)	Gea-Izquierdo	−0.45 (−0.56; −0.34)	−0.09 (−0.12; −0.07)	**−41.0**	−41.1
	Gomez-Reys	−0.21 (−0.31; −0.11)	−0.04 (−0.06; −0.02)	−28.3	**−29.4**
	Oliver	−0.29 (−0.35; −0.23)	−0.03 (−0.04; −0.01)	**−36.5**	−15.2
	Schnabel	−0.42 (−0.51; −0.34)	−0.09 (−0.14; −0.04)	**−26.0**	−4.9
	Belsky	−0.07 (−0.09; −0.06)	−0.01 (−0.02; −0.01)	**−52.6**	−42.5
	Hailu	−0.06 (−-0.10; −0.01)	−0.01 (−0.01; 0.00)	**11.2**	13.2
N (%)	Gea-Izquierdo	−0.40 (−0.65; −0.16)	−0.07 (−0.13; −0.02)	**−94.3**	−91.5
	Moreno crop	−0.30 (−0.42; −0.17)	−0.04 (−0.08; 0.00)	**1.9**	9.8
	Moreno grass	−0.25 (−0.31; −0.18)	−0.03 (−0.06; 0.00)	**−6.4**	4.4
	Moreno bush	−0.37 (−0.56; −0.19)	−0.06 (−0.08; −0.03)	6.3	**5.4**
	Schnabel	−0.07 (−0.13; −0.02)	−0.08 (−0.09; −0.06)	−54.9	**−78.0**

(continued)

Table 21.3 (continued)

Variable	Data source	β (95% CL)[a]		AIC_c	
		PDM	EDM	PDM	EDM
Soil pH	Gea-Izquierdo	−0.10 (−0.13; −0.07)	−0.02 (−0.02; −0.01)	**−40.2**	−34.2

AIC_c values in bold represent the better model
[a]Values in parenthesis represent 95% confidence limits of β e. All β estimators were unbiased (|g| < 1.0)

Any directional variation or deviations from the hypothesized distance-decay may be confirmed using the differences in β, with the caveat that the estimators are considered reasonably close to linearity. This must be confirmed using Hougaard's measure of skewness |g|. Skewness is apparent if |g| 0.25–1.0, but a parameter is considerably biased if $|g| > 1.0$ (Ratkowsky 1990). We deemed β estimators biased only if $|g| > 1.0$ (Ratkowsky 1990). When estimators are not biased, we used the β value and its 95% confidence intervals to judge the magnitude and direction of the tree effect on a given variable.

For most analyses we used the response ratio (RR) as the metric to be analysed. The is computed as U_i/C where U_i is the raw value of the measured variable under the canopy at distance i and C is the corresponding value measured in the control plot (Sileshi 2016). The advantage of RR is that it is related to biologically meaningful indices such as the relative competition intensity (= 1 − RR) used in plant ecology (Oksanen et al. 2006). The RR also makes interpretation more straightforward than other metrics especially where measurements of the same variable were given in different units (e.g. yields measured in g m^{-2} vs. t ha^{-1}). However, the use of RR may be problematic if the control plot is poorly defined as is the case in the literature reviewed. The majority of studies treated open fields or plots located farthest from the tree trunk as control plots. In some studies, anything beyond the drip line was treated as the control, although such plots can be within the tree root influence (Fig. 21.1). Therefore, wherever we thought the use of RR is problematic, we analysed the actual measurement.

We compared the performance of the PDM with the EDM using the bias-corrected Akaike information criterion (AIC_c) as well as the predictions and their 95% confidence limits. For studies with less than 5 distance classes ($N < 5$), the AIC_c cannot be estimated because the degrees of freedom are fewer relative to the parameters (p) to be estimated and the denominator ($N - p - 1$) in the AIC_c equation becomes zero. As such the AIC_c is undefined for.

$$AIC_c = AIC + \frac{2p(p+1)}{N-p-1} \tag{21.3}$$

Therefore, we did not present analyses of studies with $N < 5$.

21.3 Results and Discussion

21.3.1 Emergent Patterns

21.3.1.1 Light Availability and Soil Temperature

The two datasets on light availability, namely light transmitted through holm oak canopy (Fig. 21.3a) and light intensity under *Eucalyptus* (Fig. 21.3b) followed the same pattern of distance-decay. Similarly, soil temperature at 12:00 h and 15:00 h in the canopy of *Acacia* trees increased with increasing distance from the tree trunk (Fig. 21.3c, d). The AICc indicated that PDM predictions are better than EDM for datasets (Table 21.1). The models did not fit the soil temperature data smoothly

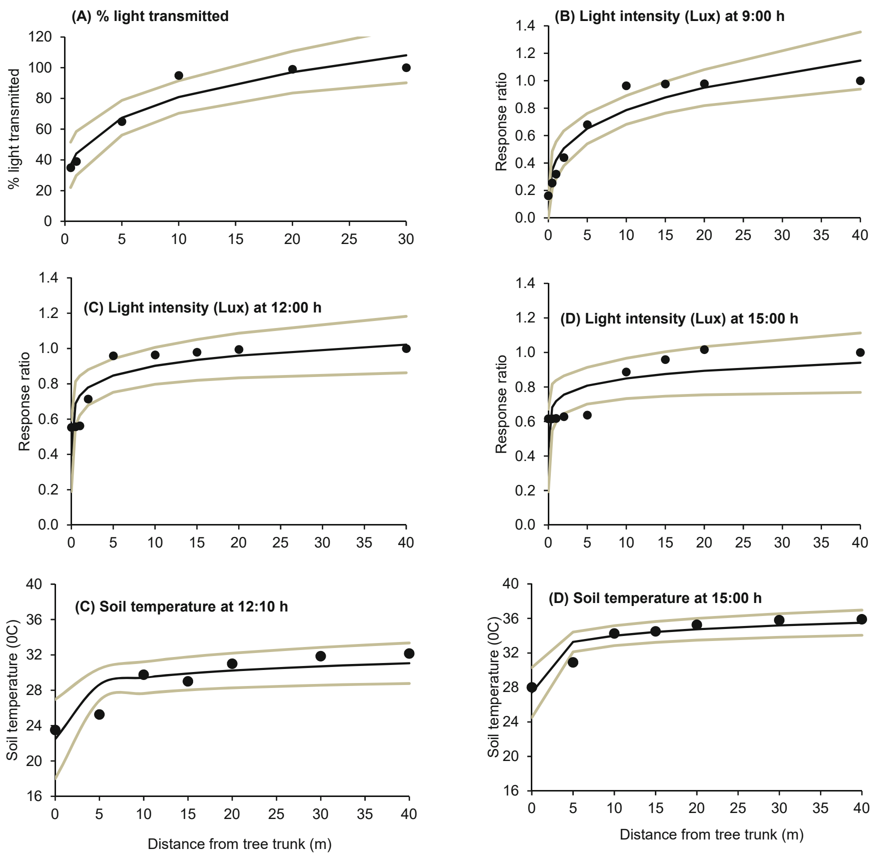

Fig. 21.3 Distance-decay of light intensity in the morning under *Eucalyptus* (**a**, **b**) in Ethiopia (data from Alemie 2009); soil temperature under *Acacia tortilis* at 12:00 h and 15:00 ha (**c**, **d**) in Kenya (data from Belsky et al. 1989). Circles, black lines and grey lines represent measured values, predictions and their 95% confidence limits generated using the power function, respectively

(Fig. 21.3c, d) due to the sparse sampling between the 0 and 10 m distance relative to the other distance classes.

21.3.1.2 Crop and Pasture Productivity

Seven datasets were available on the negative effects of trees on crop yields resulting from allelopathy (Table 21.1). In all seven datasets, crop yield showed a consistent trend of increase ($\beta > 0$) with distance from the tree (Fig. 21.4) conforming more to PDM than EDM (Table 21.1). On the other hand, positive effects ($\beta < 0$) of trees on grass yield and phytomass were found in four datasets, and in all cases distance-decay of the tree effect was confirmed (Table 21.2, Fig. 21.6). Based on the AICc values, the EDM described the co-variation between grass yield and distance better than the PDM (Table 21.2).

Trees can either depress ($\beta > 0$) or increase ($\beta < 0$) crop and grass productivity, but the distance-decay pattern still holds. Our models predict that the negative effects of tree are monotonically decreasing function of distance from the tree. Here we have demonstrated that effects arising from competition for light, nutrients and water resources or allelochemicals fit this distance-decay pattern. Trees such as *Eucalyptus* spp. are known to have negative effect on crops by lowering soil moisture content, by making the soil hydrophobic (water repellent) and reducing light interception by the crop (Alemie 2009). *Eucalyptus*, *Populus* and *Juglans* spp. are well-known to produce allelopathic substances that depress yields of understory crops due to phytotoxicity (Batish et al. 2008; Jose and Gillespie 1998; Singh and Kohli 1992). Under such situations, an inverse relationship is expected between crop yield and amount of phytotoxins (Singh and Kohli 1992). As a result, crop yields are lowest around the tree where the amounts of allelochemicals are the highest but yields will increase with distance consistent with PDM or EDM. Many other trees, however, increase crop yields through their facilitative effects (Sileshi 2016; Moreno et al. 2007; Marcos et al. 2007).

The effect of trees on forage production may be negative or positive depending on the tree species. For example, Frost and Edinger (1991) reported reduction in total annual herbage production under interior live oak (*Quercus wislizenii*) compared to blue oak (*Quercus douglasii*) canopies in the central Sierra Nevada foothills. This difference occurred regardless of the fact that the same level of soil improvement occurs under both species relative to the open areas. The reduction in herbage production under interior live oak was attributed to the effects of shading by its evergreen canopy (Frost and Edinger 1991). The improvement in grass production under tree canopies is often attributed to increased nutrient and moisture availability, improved microclimate and reduced evapotranspiration (Abdallah et al. 2012; Frost and Edinger 1991; Grouzis and Akpo 1997; Ludwig et al. 2004; Moreno et al. 2007; Moreno and Pulido 2009). By reducing wind velocity, solar radiation, air and soil temperature, and increased litter inputs on the soil trees can decrease potential evapotranspiration favouring moisture retention in the shaded area (Grouzis and Akpo 1997), which often extends beyond the canopy. For example, the patterns in

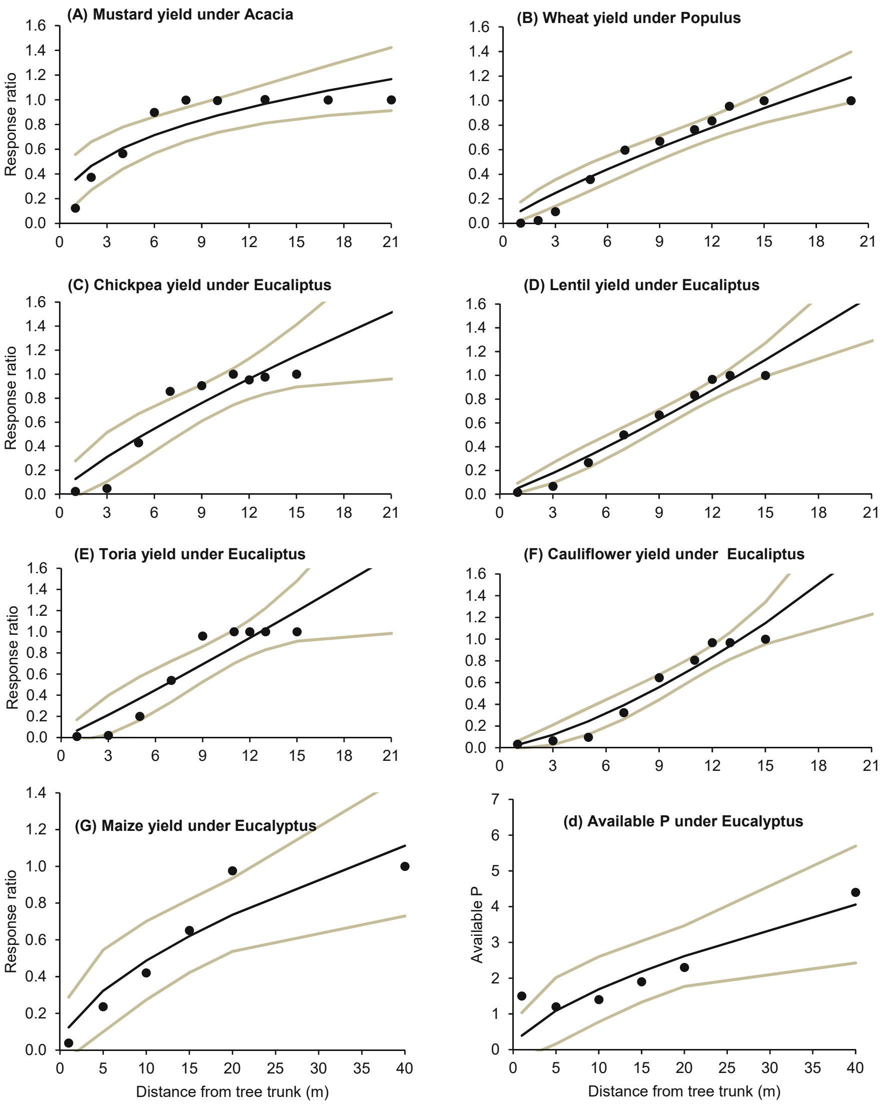

Fig. 21.4 Distance-decay of (**a**) mustard yield under *Acacia* in India (data from Yadav et al. 1993); (**b**) wheat yield under *Populus* in India (data from Singh et al. 1998); (**c–f**) wheat, chickpea, lentil, toria and cauliflower yields under *Eucalyptus* in India (data from Singh and Kohli 1992); and (**g**) maize grain yield under *Eucalyptus* in Ethiopia (data from Alemie 2009). Circles, black lines and grey lines represent measured values, predictions and their 95% confidence limits generated using the power function, respectively

litter biomass distribution are similar to those observed with grass and herbage yields. The effects of trees on litter inputs can drive patterns in soil organic matter, SOC stocks and biological activity (Howlett et al. 2011; Oliver et al. 2006).

21.3.1.3 Lateral Root Distribution

The number of lateral roots of *Parkia biglobosa* in the 0–50 cm soil depth was consistent with predictions of PDM but less so with EDM (Fig. 21.5a; Table 21.2). The available data show that the tree roots extended to at least 10 m from the trunk, but our predictions show that lateral roots could extend up to 16 m (Fig. 21.5a). The predicted number of roots at 16 m was 90.6 (95% CL: 82.2–99.0 m^{-2}), which was not significantly different from the observed number of 94 roots m^{-2} at 10 m from the trunk.

The patterns in lateral root density of *Parkia* (the only species for which adequate data are available so far) are similar to the patterns of fine root distribution of holm oak in Spanish dehesas recorded by Moreno et al. (2005). The data in Moreno et al. (2005) were recorded at only for four distances from the trunk. Therefore, we were unable to establish whether PDM or EDM fits their data. Mechanistic models of agroforestry (e.g. WaNuLCAS) assume a negative exponential decrease (i.e. EDM) in the distribution of lateral root densities (Mulia and Dupraz 2006). Our results provided greater support for PDM than EDM for *Parkia* root distribution. Nevertheless, we do not rule outs deviations from PDM as some plasticity in lateral root distribution can occur in response to heterogeneity in the soil environment or management practices. For example, in a Mediterranean climate in France, Mulia

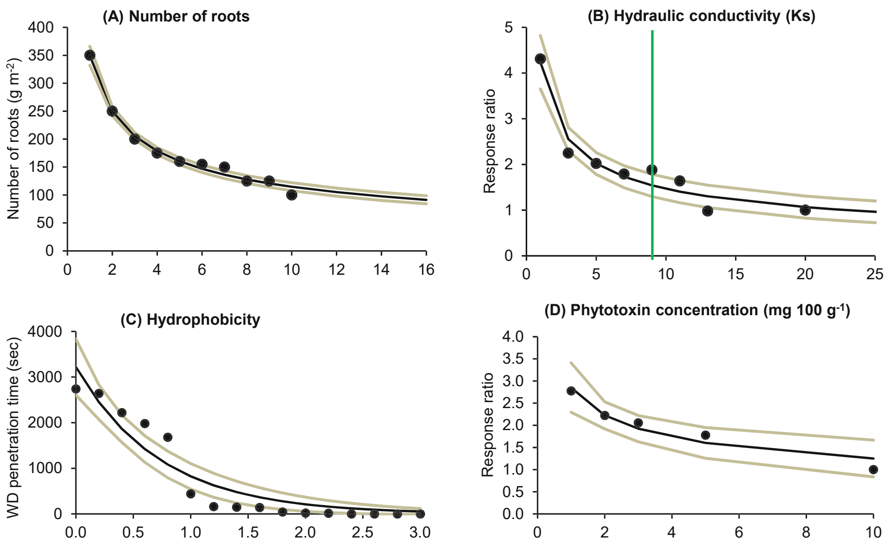

Fig. 21.5 Distance-decay of (**a**) *Parkia biglobosa* roots in Burkina Faso (data from Tomlinson et al. 1998); (**b**) saturated hydraulic conductivity of soils under *Quercus robur* in the UK (data from Chandler and Chappell 2008); (**c**) hydrophobicity of soils under *Eucalyptus* in Ethiopia (data from Alemie 2009); (**d**) phytotoxin concentrations under *Eucalyptus* in India (data from Singh and Kohli 1992); (**e**) light transmitted through *Quercus ilex* canopy in Spain (data from Montero et al. 2008). Circles, black lines and grey lines represent measured values, predictions and their 95% confidence limits generated using the power function, respectively

and Dupraz (2006) observed patterns similar to those of *Parkia* in the fine root profiles in pure stands of hybrid walnut (*Juglans regia*) and poplars (*Populus euramericana*). However, deviations were noted under intercropped trees.

Our results and the literature reviewed also suggest that the lateral root distribution of trees exceeds two times their crown radius. For example, the lateral roots of *Parkia* could extend beyond 16 m (Fig. 21.3a) while the crown radius is 7.02 m (Tomlinson et al. 1998). Similarly, the root system of holm oak explores a soil volume of >20 m distance and >4 m depth (Marcos et al. 2007), with maximum distance of 33 m off the trunk for trees with average canopy width of 10.4 m (Moreno et al. 2005). Indeed, the surface of soil explored by holm oak roots exceeds 7 times the crown projection area (Moreno et al. 2005). Our analysis of hydraulic conductivity (K_s) also demonstrated that the tree effect extended several meters beyond the canopy. This is attributed to creation of well-connected pores by both living and decayed roots, which increases the flow of water (Chandler and Chappell 2008).

The root length densities of oak trees and herbaceous plants show some overlap in the 0–90 cm soil depth even at 20 m beyond the canopy for trees with canopy radii of 7–12 m (Marcos et al. 2007). Nevertheless, holm-oak trees have a much lower root length density (mean 2.4 km m^{-3}) than herbaceous vegetation (23.7 km m^{-3}) in the first 10 cm soil depth (Moreno et al. 2005). Thus, competition for soil resources between trees and the herbaceous understory is probably not as strong as usually assumed (Moreno et al. 2005). However, the tree roots may initiate complex interactions with roots of associated crops or grass as well as mycorrhizae and rhizosphere microflora. This will have implications for uptake of water and nutrients even 20 m beyond the canopy. For example, the roots of trees and associated crops may be interconnected by mycorrhizae thus increasing the likelihood of crop uptake of immobile nutrients (e.g. phosphorus) and availability of moisture.

There is also a growing body of evidence suggesting that trees in savannas can easily avoid competition with grasses for water and nutrients due to niche separation, i.e., due to differences in phenology and rooting systems of trees and grass (Marcos et al. 2007). For example, in Dehesas, crops and grasses take water mostly from the top 40 to 60 cm of soil, whereas holm-oak can extract water from 3 to 13 m depths (Moreno and Pulido 2009). An emergent feature of vegetation in drylands is spatial self-organization (Gilad et al. 2007; Klausmeier 1999; Tzuk et al. 2020) arising from positive feedback loops between local vegetation growth and water transport towards the growth location (Meron 2018). The redistribution of water by patterned vegetation can increase the resilience of the ecosystem to prolonged droughts by providing an extra source of water that vegetation patches draw from their bare-soil surroundings (Meron 2018; Tzuk et al. 2020). Therefore, the root influence of trees is likely to be underestimated when the crown projection area is used to define the trees influence on soil and understory vegetation.

21.3.1.4 Hydraulic Conductivity

Analysis of the dataset on saturated hydraulic conductivity of soils under *Quercus robur* revealed distance-decay of tree effects consistent with our hypothesized models (Table 21.2; Fig. 21.5b). Comparison of the models in terms of raw data and RRs resulted in similar β values and their 95% CL for each model. In terms of AIC_c, the EDM outperformed PDM when the geometric means were analysed, but the reverse was true when median values were analysed. Skewness was also apparent ($|g| > 0.25$) for EDM when median values were used. In the case of PDM, there was no significant loss in information (AIC_c) when either the geometric mean or RR was analysed. Our predictions using PDM show that the tree roots extend 2–3 times the crown radius. For example, the predicted geometric mean K_s at 20 m (1.37; 95% CL: 0.80–1.85) was not significantly different from K_s of 1.42 recorded at the drip line (Fig. 21.5b).

21.3.1.5 Hydrophobicity and Allelochemicals

Hydrophobicity (water repellence) of field-dried soil followed a clear decay with distance from the trunks of *Eucalyptus* tree (Fig. 21.5c, Table 21.2) although the fit of the PDM was poorer than expected. Soils were over 53,000 times more hydrophobic at 20 cm, 440 times more at 1 m and 20 times more at 2 m around the tree than at 3 m from the trunk. The concentration of phytotoxins showed a distance-decay trend similar the one observed with hydrophobicity (Fig. 21.5d).

21.3.1.6 Litter Biomass, Soil Organic Carbon (SOC) and Nutrients

Total litter biomass and herbaceous litter biomass under *Eucalyptus* (Fig. 21.5d, e) and *Milletia* (Fig. 21.5f) trees declined with distance from the tree trunk. In both cases, the EDM fitted the data better than PDM (Table 21.3). However, herbaceous litter biomass (Fig. 21.5e) showed a weaker pattern ($\beta = -0.31$) than total litter biomass ($\beta = -0.60$). In the case of *Milletia* (Fig. 21.5f), the model did not fit the data smoothly due to the lack of sampling between the 5 and 30 m distance.

SOC content showed a common trend of distance-decay in all five datasets (Fig. 21.7). The PDM fitted the data better than EDM in five out of the six datasets analysed (Table 21.3). The β values of the PDM fell within a narrow range of -0.06 to -0.45 (Table 21.3). In the case of SOC under *Acacia* (Fig. 21.7), the model did not fit the data smoothly due to the sparse sampling between the 0 and 10 m distance relative to the other distance classes. Our models predict distance-decay of SOC, with positive effect of trees on SOC (but negative effect on bulk density) extending several meters into the open area. Earlier reports (e.g. Amiotti et al. 2000; Gallardo et al. 2000; Howlett et al. 2011; Simón et al. 2012; Yadessa et al. 2009) have reported a common pattern of higher SOC concentrations under the trees than in adjacent open areas. Unlike most of these reports, our models predict that spatial heterogeneity in SOC forms a continuum of influence circles around the tree. Similarly, a Universal Kriging model revealed that the correlation peaks around 4 m, indicating the existence of an influence area around trees where higher SOC concentrations are found (Simón et al. 2012). Thus, the spatial patterning in SOC elucidated in this study can help in developing sampling schemes and models for accurate estimation of ecosystem carbon in support of international negotiations regarding climate change.

A general pattern of distance-decay in soil total nutrients similar to that of SOC was also evident in the data we analysed. With β values ranging between -0.07 and -0.40, trees also had significantly positive effects on soil total N content in all five datasets (Table 21.3). Using geostatistical analysis, Gallardo (2003) established that SOC and mineral-N show very similar ranges (the distance at which samples remain spatially correlated) of 9.5 to 9.7 m in a dehesa. In terms of the AIC_c (Table 21.3) and the 95% CIs of predictions, the PDM fitted the data better than the EDM in three out of the five datasets (Fig. 21.8). Under *Acacia tortilis* and *Adansonia digitata* trees in Kenya, the concentrations of soil P, Ca and K declined with distance from the tree trunk (data not shown). On the other hand, under Eucalyptus in Ethiopia, soil available P and exchangeable calcium concentrations increased with increased distance from the tree trunk (Fig. 21.8).

Phosphorous and Na concentrations showed higher ranges (13–13.4 m), with the lowest range being 3.8 m for K (Gallardo 2003). A number of other data not analysed here due to the small sample sizes also reveal that soil P, Ca^{2+}, K^{+}, Mg^{2+} and CEC show the same patterns of distance-decay in dehesas (Gallardo 2003; Moreno and Obrador 2007; Moreno et al. 2007), savannas and agroforestry parklands in Africa (Belsky et al. 1989; Sileshi 2016) and paddocks in Australia (Eldridge and Wong 2005; Wilson 2002). The enhancement of soil nutrients is greatest in the upper 30 cm of the soil, and this extends to approximately two canopy radii from the tree trunk (Schnabel et al. 2013).

21.3.1.7 Soil pH

As in soil nutrients, pH declined with distance from the trunk consistent with PDM (Table 21.3; Fig. 21.8). Eldridge and Wong (2005) and Wilson (2002) found a similar pattern under Eucalypt paddock trees in Australia, but we were unable to fit our models to their data. In an African savanna, Belsky et al. (1989) found more acid soil at the base of Acacia trees. Although acidification of the surface soil occurs below the entire tree canopy, alteration is most severe in proximity to the trunk (Amiotti et al. 2000). This has been mainly attributed to stemflow and but bark litter near the trunk (Zinke 1962). The acidity of stemflow is mostly due to the charge of water-soluble phenolic substances leached from bark and their chelating properties (Beniamino et al. 1991). Soils under the inner ring of bark litter also exhibit evidence of acid hydrolysis of primary silicates (Amiotti et al. 2000).

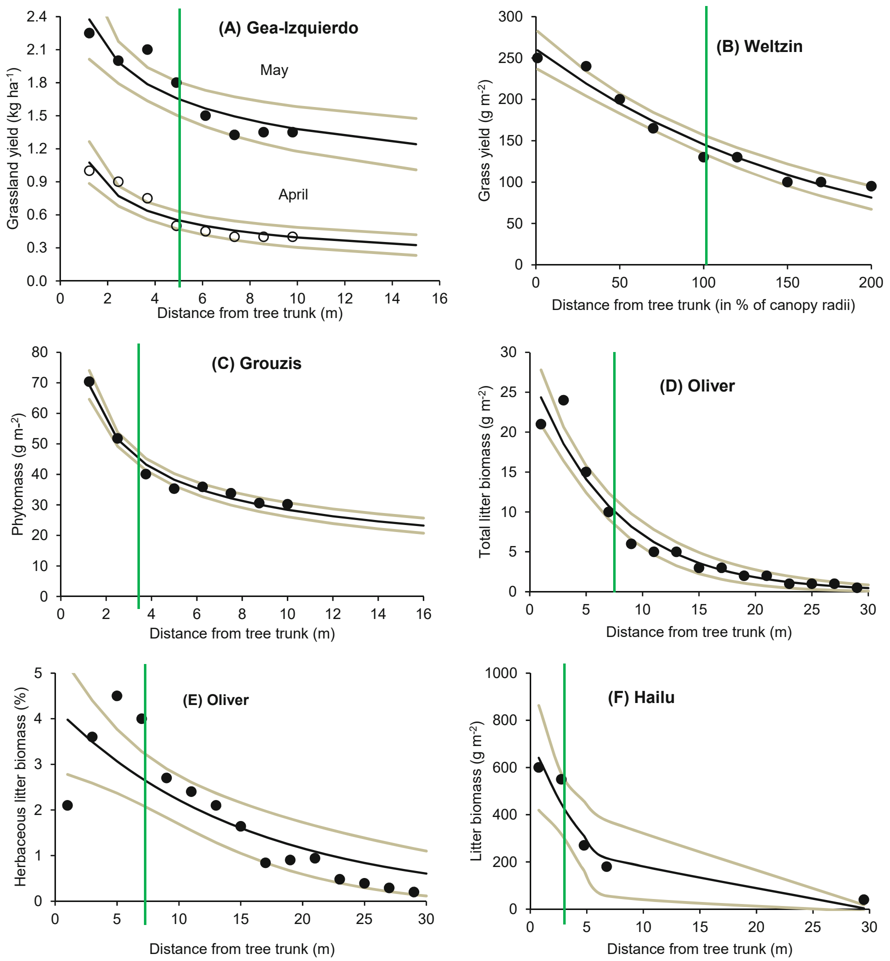

Fig. 21.6 Distance-decay of (**a**) grass yield under *Quercus* in Spain (data from Gea-Izquierdo et al. 2010), and (**b**) grass yield under *Acacia* and *Balanites* in Senegal (data from Grouzis and Akpo 1997); (**c**) grass yield under *Acacia* in Kenya (data from Weltzin and Coughenour 1990); (**d**) total litter biomass and (**e**) herbaceous litter biomass under *Eucalyptus* in Australia (data from Oliver et al. 2006); and (**f**) litter biomass under *Milletia* in Ethiopia (data from Hailu et al. 2000). Circles, black lines and grey lines represent measured values, predicted lines and their 95% confidence limits generated using the power function, respectively. Predictions between 10 and 16 m are extrapolations. The vertical green line represents the drip line

An emergent pattern from all of the datasets analysed (Figs. 21.3, 21.4, 21.5, 21.6, 21.7 and 21.8) was the ability of the distance-decay models to adequately simulate the measured values. This indicates the predictability of effects of isolated trees in a variety of settings. In 21 out of 33 cases analysed, the PDM described single-tree effects better than the EDM. Thus, the results support our hypotheses that

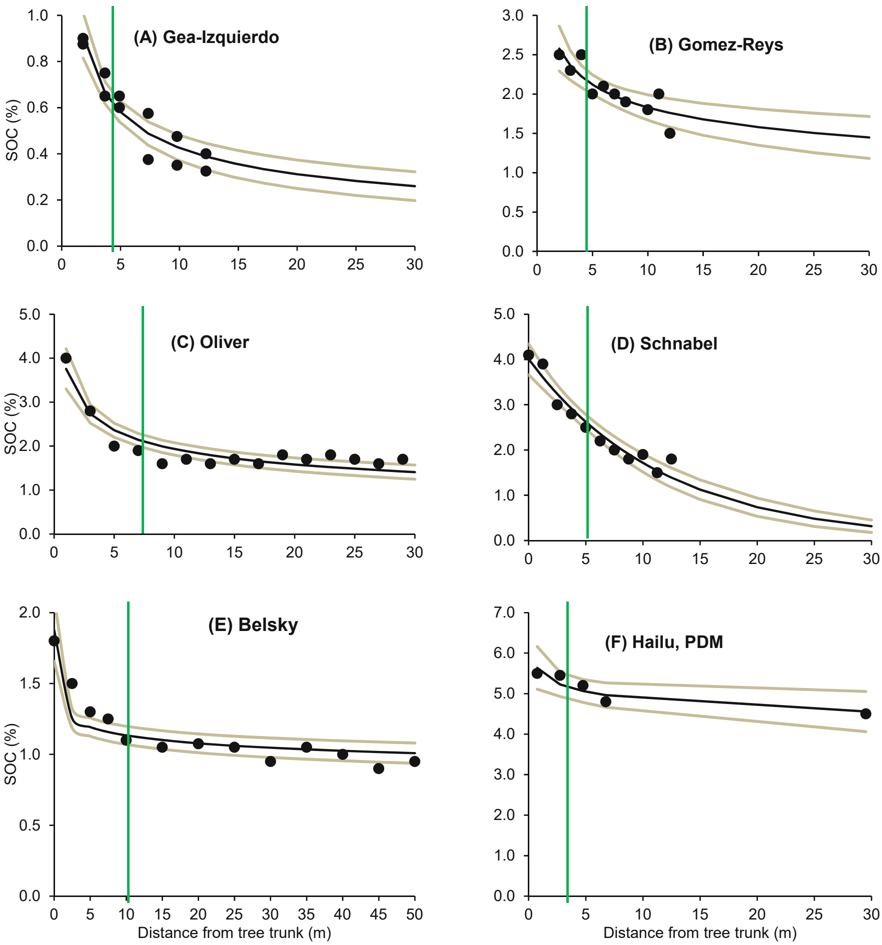

Fig. 21.7 Distance-decay of soil organic carbon under (**a**) *Quercus* in Spain (data from Gea-Izquierdo et al. 2010), (**b**) *Quercus* in Portugal (data from Gómez-Rey et al. 2011); and (**c**) *Eucalyptus* in Australia (data from Oliver et al. 2006); (**d**) *Quercus douglasii* in USA (data from Schnabel et al. 2013); (**e**) *Acacia* in in Kenya (data from Belsky et al. 1989); and (**f**) under *Milletia* in Ethiopia. Solid circles, black lines and grey lines represent measured values, fitted lines and their 95% confidence limits. In **a** and **b**, predictions between 12 and 30 m are extrapolations. The vertical green line represents the drip line

single-tree effects are monotonically decreasing functions of distance from the trunk. However, the explanations for these patterns may differ with the variable under study.

The observed pattern may arise due to above and belowground organic matter inputs from the tree and associated vegetation, nutrient cycling and protection of soil nutrient from erosion loss. Some of the soil nutrients may have been transported to the canopy zone from surrounding soils by the lateral roots or deposited in dung by

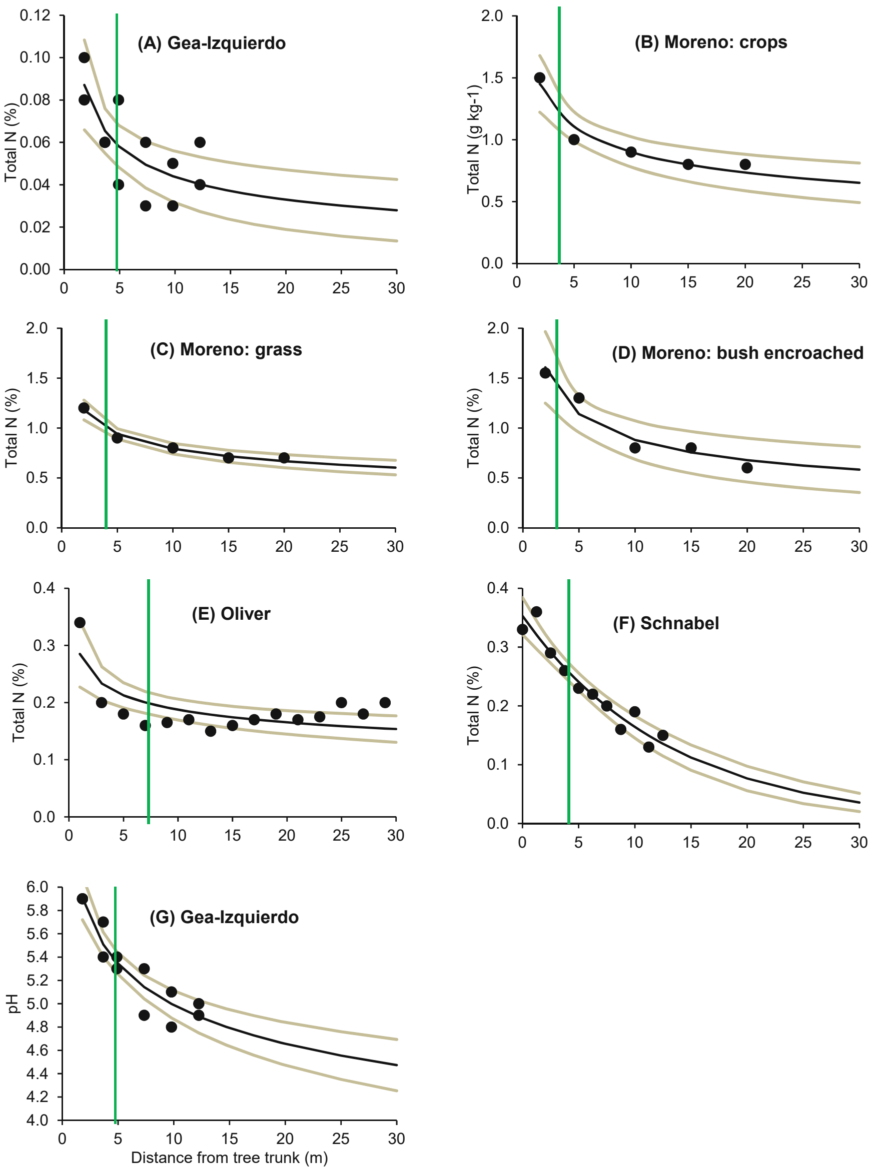

Fig. 21.8 Distance-decay in soil nitrogen content (%) (**a**) under *Quercus* in Spain (data from Gea-Izquierdo et al. 2010); (**b**, **c** and **d**) crops, grass and bush encroached plots under *Quercus* in Spain (data from Moreno and Obrador 2007); (**e**) under *Eucalyptus* in Australia (data from Oliver et al. 2006); (**f**) under *Quercus* in USA (data from Schnabel et al. 2013); and (**g**) soil pH in under *Quercus* in Spain (data from Gea-Izquierdo et al. 2010); Solid circles, black lines and grey lines represent measured values, fitted lines and their 95% confidence limits generated using power (left) and exponential distance-decay functions. In (**a**–**d**), predictions between 12 and 30 m are extrapolations from the model. The vertical green line represents the drip line

birds and mammals that utilize the tree (Belsky et al. 1989). Trees can also pump nutrients from deep soil horizons, which are then recycled via leaf litter (Sileshi 2016). This can concentrate nutrients around the tree. Trees are also shown to promote the development of thicker topsoil horizons through addition of organic matter and nutrient cycling (Schnabel et al. 2013). Therefore, it is not surprising that isolated trees create islands of soil fertility and high quality (Belsky et al. 1989; Eldridge and Wong 2005; Rhoades 1997; Schnabel et al. 2013). From an ecological perspective, these islands can serve as keystone structures and important local and regional nutrient reserves that can influence community structure and ecosystem functions (Rhoades 1997).

21.3.2 Unifying Perspectives and Theory

The distance-decay patterns established in this study are consistent with the concepts of 'influence circles' (Zinke 1962) and ecological field theory (Li et al. 2000). 'Influence circles' defines the predictable variation in soil properties as a function of the distance from the axes of trees often observed in forest stands (Zinke 1962; Boettcher and Kalisz 1990). Zinke (1962) postulated that in the absence of external variables such as wind and steep slope, the properties of the soil under the tree's influence will develop in a symmetrical pattern around each tree. Thus, each tree has an influence circle roughly proportional to the size of the crown projection area on the soil surface. The tree has a maximum influence under the canopy and the influence decreases outward from the tree (Boettcher and Kalisz 1990). However, Zinke's (1962) definition oversimplifies the patterns because it limits the tree's influence to the canopy effects and conceptualizes three concentric circles; bark, litter and outside zones of influence. In reality, these circles intergrade due to the movement and mixing of bark, litter and vegetation due to various forces. This concept also does not recognize the facilitative and negative effects of lateral roots that extend several meters beyond the crown projection area. Therefore, we propose that the definition of 'influence circles' to be relaxed to include the root zone of influence.

Ecological field theory (EFT) was originally introduced by Wu et al. (1985) as a theoretical framework to account for the effect of competition by forest trees on the growth of a subject tree or neighbouring vegetation. EFT models express the effect of trees on a given point X in the space as an exponential function of individual tree properties and the point's distance to neighbouring trees (Liu and Halvorsen 2012). The individual tree is considered to be surrounded by a circular field of influence (called ecological field), where the tree affects the availability of resources according to its own characteristics and other environmental factors. As the tree adds or subtracts resources, it either improves or suppresses the growth of other plants in its zone of influence. Predictions of PDM are consistent with EFT, and thus our findings provide a mechanistic explanation for the EFT. If the exponential function is replaced by the power-law function as the default model, the EFT can be a unifying theory for tree influences in various settings.

21.3.3 Implications for Conservation and Management

The results of this analyses support the growing realization that large old trees are keystone structures in the landscapes where they occur (Hall and Bunce 2011; Lindenmayer et al. 2012, 2014; Manning et al. 2006; Mouquet et al. 2013; Stagoll et al. 2012). Keystone structures are defined as distinct spatial structures providing resources, shelter or goods and services crucial for other species (Mouquet et al. 2013). According earlier of reviews, large isolated trees play a disproportionately large role in generating habitat diversity, maintaining plant species richness and providing shade, shelter and resting places for wild animals (Dean et al. 1999). This perspective can be useful for instituting policies and practice to guide conservation agencies and land owners to protect and manage single tree stands (Lindenmayer et al. 2014). In natural ecosystems, it is important to maintain the population structure of key tree species especially in the oligotrophic arid savannas and critical habitats. Oligotrophic savannas are savannas that occur in nutrient-poorenvironments. In managed ecosystems, land owners often remove or excessively prune trees, for example in dehesas/montados (Pinto-Correia and Mascarenhas 1999; Plieninger et al. 2003) in the hope of improving grass productivity. They also engage in excessive control of shrub under the trees although shrubs play a key role in the natural regeneration of oaks (Moreno and Obrador 2007). Even if the trees do not increase pasture productivity, the spatial variability they create may play a critical role in maintaining other ecosystem functions by concentrating limiting resources. In the past, systematic planting of trees has been widely promoted in agroforestry. The review of the literature and the analyses has highlighted the value of isolated trees in various systems. Recently Tzuk et al. (2020) showed that in contrast to the widespread practice of planting the woody and herbaceous species in alternating rows (or stripe pattern), hexagonal patterns increase the system's resilience to droughts, while maintaining higher crop yields of annuals.

21.3.4 Implications for Study Design and Analysis

The results also have implications for study design and analysis. In the past, inferences about single-tree effects were based mainly on study designs where distance classes are used as fixed effects in regression and analysis of variance (ANOVA) models. The distance-decay in measured variables indicates that observations around trees are spatially structured. In the presence of spatial structure and autocorrelation, conventional sampling and statistical methods are inappropriate. However, researchers still use conventional design-based sampling and classical statistics which assume that observations are identically and independently distributed. A common study design involved comparing plots under the tree canopy with those outside the canopy, assuming the crown projection area as the limiting zone for defining the control plots. Another common practice has been comparing plots under the canopy, drip line and the open area. Such comparisons often assume that the area under the canopy is homogeneous, and that measurements under the canopy, drip line and the open area are discrete. They also ignore the effect of distance, direction and the correlation between neighbouring samples. Other studies take measurements at different distances, and then apply correlation analysis or linear regression to establish the relationship between measured variables and the distance from tree bases (e.g. Oliver et al. 2006; Wilson 2002; Yadav et al. 1993). ANOVA and regression assume that measured variables are identically and independently distributed among distance classes. In reality, the measurements in the different distance classes and directions are not independent as observations that are closer together show spatial autocorrelation due to their neighbouring physical locations. Another problem with ANOVA arises because of unequal number of observations in the open area, which are often fewer than under the canopy. The standard *F*-test was originally designed for balanced designs (samples of equal size) and assumes equality of variance. Results from *F*-test can be unreliable when samples of unequal size are combined with unequal variance and spatial dependence. Therefore, ANOVA is inadequate to model single-tree effects, which are often monotonic functions of distance. Another concern is the use of the tree canopy vertical projection as limiting zone in defining the control plots. The majority of studies used open fields or plots located farthest from the tree trunk as controls. As demonstrated here, the tree's influence through canopy light interception may greatly exceed the drip line. Due to root activity, the influence of the tree may extend what is considered outside the canopy. Review of the literature shows that canopy spread is not a good predictor of root spread, or conversely root distribution may not correspond to canopy distribution especially for older trees. Tree roots may extend to treeless zones up to 60 m from tree trunks. Even plots located 5–10 times the crown radius far may not be true controls unless trenching is used. The use of extensive treeless areas as controls may also give rise to dissimilarity in soil conditions. Therefore, we discourage the common practice of establishing sampling plots randomly around the tree and the binary comparisons of measurements under the tree canopy with those in the open areas. We also discourage the use of distance as a fixed effect in statistical models when analysing data from agroforestry systems. We strongly recommend application of model-based geospatial sampling and analyses.

21.4 Conclusions

Despite the large differences in tree species and their growing environment, their influence on ecosystem properties followed remarkably similar spatial patterns across a wide range of ecosystems. Therefore, it is concluded that single-tree influences follow predictable patterns in measured variables, and that the spatial heterogeneity under trees and the open area is a continuum. It is also concluded that tree effects exceed the crown projection area, and therefore, the contribution of isolated tree stands to ecosystem functioning may be disproportionately larger than the area they occupy. The results provide support to the claim that isolated trees can serve as keystone structures in the landscape. This provides a justification for preservation and prudent management of isolated trees in the landscapes where they occur. It also provides a theoretical basis for a paradigm shift in study design and data analysis.

References

Abdallah F, Noumi Z, Ouled-Belgacem A, Michalet R, Touzard B, Chaieb M (2012) The influence of *Acacia tortilis* (Forssk.) ssp. *raddiana* (Savi) Brenan presence, grazing, and water availability along the growing season, on the understory herbaceous vegetation in southern Tunisia. J Arid Environ 76:105–114

Abrams MM, Jacobson PJ, Jacobson KM, Seely MK (1997) Survey of soil chemical properties across a landscape in the Namib desert. J Arid Environ 35:29–38

Alemie TC (2009) The effect of *eucalyptus* on crop productivity, and soil properties in the Koga watershed, western Amhara region, Ethiopia. MSc. Thesis, Cornell University, USA

Amiotti NM, Zalba PL, Sánchez F, Peinemann N (2000) The impact of single trees on properties of loess-derived grassland soils in Argentina. Ecology 81:3283–3290

Austin-Petersen A, Larson N, Neufeld D (2002) *Quercus macrocarpa* has no significant effect on surrounding soil in restored savannas. Tillers 3:1–4

Ayres E, Steltzer H, Berg S, Wallenstein MD, Simmons BL et al (2009) Tree species traits influence soil physical, chemical, and biological properties in high elevation forests. PLoS One 4(6): e5964

Bak P, Tang C, Wiesenfeld K (1987) Self-organized criticality: an explanation of the 1/f noise. Phys Rev Lett 59:381–384

Barbier N, Couteron P, Lefever R, Deblauwe V, Lejeune O (2008) Spatial decoupling of facilitation and competition at the origin of gapped vegetation patterns. Ecology 89:1521–1531

Batish DR, Singh HP, Kohli RK (2008) Allelopathic tree–crop interactions under agroforestry systems. In: Batish DR, Kohli RK, Jose S, Singh HP (eds) Ecological basis of agroforestry. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp 37–47

Belsky AJ, Amundson RG, Duxbury JM, Riha SJ, Ali AR, Mwonga SM (1989) The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. J Appl Ecol 26:1005–1024

Beniamino F, Ponge JF, Arpin P (1991) Soil acidification under the crown of oak trees. I. Spatial distribution. For Ecol Manage 40:221–232

Boettcher SE, Kalisz PJ (1990) Single-tree influence on soil properties in the mountains of eastern Kentucky. Ecology 71:1365–1372

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa. FAO conservation guide 34. Rome, Italy

Chandler KR, Chappell NA (2008) Influence of individual oak (*Quercus robur*) trees on saturated hydraulic conductivity. For Ecol Manage 256:1222–1229

Chen YG (2015) The distance-decay function of geographical gravity model: power law or exponential law? Chaos Soliton Fractals 77:174–189

Chiatante D, Scippa SG, Di Iorio A, Sarnataro M (2002) The influence of steep slopes on root system development. J Plant Growth Reg 21:247–260

Dean WRJ, Milton SJ, Jeltsch F (1999) Large trees, fertile islands, and birds in arid savanna. J Arid Environ 41:61–78

den Herder M, Moreno G, Mosquera-Losada RM, Palma JHN, Sidiropoulou A, Freijanes JJS et al (2017) Current extent and stratification of agroforestry in the European Union. Agric Ecosyst Environ 241:121–132

Dey DC, Kabrick JM, Schweitzer CJ (2017) Silviculture to restore oak savannas and woodlands. J For 115:202–211

Eldridge DJ, Wong VNL (2005) Clumped and isolated trees influence soil nutrient levels in an Australian temperate box woodland. Plant and Soil 270:331–342

Estes LD, Searchinger T, Spiegel M, Tian D, Sichinga S, Mwale M et al (2016) Reconciling agriculture, carbon and biodiversity in a savannah transformation frontier. Phil Trans R Soc B 371:20150316

Frost WE, Edinger SB (1991) Effects of tree canopies on soil characteristics of annual rangeland. J Range Manage 44:286–288

Gallardo A (2003) Effect of tree canopy on the spatial distribution of soil nutrients in a Mediterranean Dehesa. Pedobiologia 47:117–125

Gallardo A, Rodríguez-Saucedo JJ, Covelo F, Fernández-Alés R (2000) Soil nitrogen heterogeneity in a Dehesa ecosystem. Plant and Soil 222:71–82

Gea-Izquierdo G, Allen-Díaz B, San Miguel A, Cañellas I (2010) How do trees affect spatio-temporal heterogeneity of nutrient cycling in Mediterranean annual grasslands? Ann For Sci 67: 112

Gebrewahid Y, Gebre-Egziabhier TB, Teka K, Birhane E (2018) Carbon stock potential of scattered trees on farmland along an altitudinal gradient in Tigray, Northern Ethiopia. Ecol Process 7:40

Gilad E, Shachak M, Meron E (2007) Dynamics and spatial organization of plant communities in water-limited systems. Theor Popul Biol 72:214–230

Gómez-Rey MX, Garcês A, Madeira M (2011) Organic C distribution and N mineralization in soil of oak woodlands with improved pastures. Revista de Ciencias Agrarias 34(1):80–92

Grouzis M, Akpo L-E (1997) Influence of tree cover on herbaceous above- and below-ground phytomass in the Sahelian zone & Senegal. J Arid Environ 35:285–296

Hailu T, Negash L, Olsson M (2000) *Millettia ferruginea* from southern Ethiopia: impacts on soil fertility and growth of maize. Agr Syst 48:9–24

Hall SJG, Bunce RGH (2011) Mature trees as keystone structures in Holarctic ecosystems—a quantitative species comparison in a northern English park. Plant Ecol Divers 4:243–250

Howlett DS, Moreno G, Losada MRM, Nair PKR, Nair VD (2011) Soil carbon storage as influenced by tree cover in the Dehesa cork oak silvopasture of Central-Western Spain. J Environ Monit 13:1897–1904

Hubbell SP (2001) The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton

Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) A global analysis of root distributions for terrestrial biomes. Oecologia 108:389–411

Joffre R, Rambal S, Ratte JP (1999) The dehesa system of southern Spain and Portugal as a natural ecosystem mimic. Agr Syst 45:57–79

Jose S, Gillespie AR (1998) Allelopathy in black walnut (*Juglans nigra* L.) alley cropping. I. Spatio-temporal variation in soil juglone in a black walnut–corn (*Zea mays* L.) alley cropping system in the Midwestern USA. Plant and Soil 203:191–197

Klausmeier CA (1999) Regular and irregular patterns in semiarid vegetation. Science 284:1826

Li B-L, Wu S, Zou G (2000) Self-thinning rule: a causal interpretation from ecological field theory. Ecol Model 132:167–173

Lindenmayer DB, Laurance WF, Franklin JF (2012) Global decline in large old trees. Science 338: 1305–1306

Lindenmayer DB, Laurance WF, Franklin JF, Likens GE, Banks SC, Blanchard W, Gibbons P, Ikin K, Blair D, McBurney L, Manning AD, Stein JA (2014) New policies for old trees: averting a global crisis in a keystone ecological structure. Conserv Lett 7:61–69

Liu HY, Halvorsen R (2012) Single-tree influence on understorey vegetation in five Chinese subtropical forests. iForest 5:179–187
Ludwig F, de Kroon H, Berendse F, Prins HHT (2004) The influence of savanna trees on nutrient, water and light availability and the understorey vegetation. Plant Ecol 170:93–105
Manning AD, Fischer J, Lindenmayer DB (2006) Scattered trees are keystone structures - implications for conservation. Biol Conserv 132:311–321
Marcos GM, Obrador JJ, García E, Cubera E, Montero MJ, Pulido F, Dupraz C (2007) Driving competitive and facilitative interactions in oak dehesas through management practices. Agr Syst 70:25–40
Marković D, Gros C (2014) Power laws and self-organized criticality in theory and nature. Phys Rep 536:41–74
Meron E (2018) From patterns to function in living systems: dryland ecosystems as a case study. Annu Rev Condens Mat Phys 9:79–103
Miguel JMD, Acosta-Gallo B, Gómez-Sa A (2013) Understanding Mediterranean pasture dynamics: general tree cover vs. specific effects of individual trees. Rangel Ecol Manage 66:216–223
Montero MJ, Moreno G, Bertomeu M (2008) Light distribution in scattered-trees open woodlands in Western Spain. Agr Syst 73:233–244
Moreno G, Obrador JJ (2007) Effects of trees and understorey management on soil fertility and nutritional status of holm oaks in Spanish dehesas. Nutr Cycl Agroecosyst 78:253–264
Moreno G, Pulido FJ (2009) The functioning, management and persistence of dehesas. In: Rigueiro-Rodríguez A et al (eds) Agroforestry in Europe: current status and future prospects. Springer Science + Business Media B.V, Berlin, pp 127–161
Moreno G, Obrador JJ, Cubera E, Dupraz C (2005) Fine root distribution in dehesas of Central–Western Spain. Plant and Soil 277:153–162
Moreno G, Obrador JJ, García A (2007) Impact of evergreen oaks on soil fertility and crop production in intercropped dehesas. Agric Ecosyst Environ 119:270–280
Moreno G, Bartolome JW, Gea-Izquierdo G, Cañellas I (2013) Overstory–understory relationships. In: Campos P et al (eds) Mediterranean oak woodland working landscapes, landscape series 16. Springer Science + Business Media, Dordrecht
Moreno G, Aviron S, Berg S, Crous-Duran J, Franca A, de Jalón SG et al (2018) Agroforestry systems of high nature and cultural value in Europe: provision of commercial goods and other ecosystem services. Agr Syst 92:877–891
Morlon H, Chuyong G, Condit R, Hubbell S, Kenfack D, Thomas D, Valencia R, Green JL (2008) A general framework for the distance–decay of similarity in ecological communities. Ecol Lett 11:904–917
Mouquet N, Gravel D, Massol F, Calcagno V (2013) Extending the concept of keystone species to communities and ecosystems. Ecol Lett 16:1–8
Mulia R, Dupraz C (2006) Unusual fine root distributions of two deciduous tree species in southern France: what consequences for modelling of tree root dynamics? Plant and Soil 281:71–85
Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's nationally determined contribution. J Clean Prod 281:124831
Nekola JC, McGill BJ (2014) Scale dependency in the functional form of the distance decay relationship. Ecography 37(4):309–320
Nekola JC, White PS (1999) The distance decay of similarity in biogeography and ecology. J Biogeogr 26:867–878
O'Dwyer JP, Green JL (2010) Field theory for biogeography: a spatially explicit model for predicting patterns of biodiversity. Ecol Lett 13:87–95
O'Dwyer JP, Lake JK, Ostling A, Savage VM, Green JL (2009) An integrative framework for stochastic size-structured community assembly. Proc Natl Acad Sci USA 106:6170–6175
Oksanen L, Sammul M, Mägi M (2006) On the indices of plant-plant competition and their pitfalls. Oikos 112:149–155

Oliver I, Pearce S, Greenslade PJM, Britton DR (2006) Contribution of paddock trees to the conservation of terrestrial invertebrate biodiversity within grazed native pastures. Austral Ecol 31:1–12

Palmer MW (2005) Distance decay in an old-growth neotropical forest. J Veg Sci 16:161–166

Pinto-Correia T, Mascarenhas J (1999) Contribution to the extensification/intensification debate: new trends in the Portuguese montado. Land Urban Plan 46:125–131

Pinto-Correia T, Guiomar N, Ferraz-de-Oliveira MI, Sales-Baptista E, Rabaça J, Godinho C, Ribeiro NP, Sá Sousa P, Santos P, Santos-Silva C, Simões MP, ADF B, Catarino L, Costa P, Fonseca E, Godinho S, Azeda C, Almeida M, Gomes L, de Castro JL, Louro R, Silvestre M, Vaz M (2018) Progress in identifying high nature value montados: impacts of grazing on hardwood rangeland biodiversity. Rangel Ecol Manage 71:612–625

Plieninger T, Pulido F, Konold W (2003) Effects of land-use history on size structure of holm oak stands in Spanish dehesas: implications for conservation and restoration. Environ Conserv 30: 61–70

Ratkowsky D (1990) Handbook of nonlinear regression models. Marcel Dekker, New York

Rhoades CC (1997) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agr Syst 35:71–94

Roupsard O, Audebert A, Ndour AP, Clermont-Dauphin C, Agbohessou Y, Sanoui J et al (2020) How far does the tree affect the crop in agroforestry? New spatial analysis methods in a *Faidherbia* parkland. Agric Ecosyst Environ 296:106928

Schnabel S, Dahlgren RA, Moreno-Marcos G (2013) Soil and water dynamics. In: Campos P et al (eds) Mediterranean oak woodland working landscapes. Landscape series, vol 16, pp 91–121

Siebert F, Dreber N (2019) Forb ecology research in dry African savannas: knowledge, gaps, and future perspectives. Ecol Evol 9:7875–7891

Sileshi GW (2016) The magnitude and spatial extent of *Faidherbia albida* influence on soil properties and primary productivity in drylands. J Arid Environ 132:1–14

Sileshi GW, Arshad MA (2012) Application of distance–decay models for inferences about termite mound-induced patterns in dry lands ecosystems. J Arid Environ 77:138–148

Simón N, Montes F, Díaz-Pinés E, Benavides R, Rubio A (2012) Spatial distribution of the soil organic carbon pool in a holm oak dehesa in Spain. Plant and Soil 366:537–549

Singh D, Kohli RK (1992) Impact of *Eucalyptus tereticornis* Sm. Shelterbelts on crops. Agr Syst 20:253–266

Singh HP, Kohli RK, Batish DR (1998) Effect of poplar (*Populus deltoides*) shelterbelt on growth and yield of wheat in Punjab, India. Agr Syst 40:208–213

Stagoll K, Lindenmayer DB, Knight E, Fischer J, Manning AD (2012) Large trees are keystone structures in urban parks. Conserv Lett 5:115–122

Streiling S, Matzarakis A (2003) Influence of single and small clusters of trees on the bioclimate of a city: a case study. J Arboricult 29:309–316

Teklehaimanot Z (2004) Agroforestry parkland systems in sub-Saharan Africa. Agr Syst 60:1–2

Tobler W (1970) A computer movie simulating urban growth in the Detroit region. Econ Geogr 46: 234–240

Tomlinson H, Traore A, Teklehaimanot Z (1998) An investigation of the root distribution of *Parkia biglobosa* in Burkina Faso, West Africa, using a logarithmic spiral trench. For Ecol Manage 107:173–182

Tripathi HG, Woollen ES, Carvalho M, Parr CL, Ryan CM (2021) Agricultural expansion in African savannas: effects on diversity and composition of trees and mammals. Biodivers Conserv 30:3279–3297

Tzuk O, Uecker H, Meron E (2020) The role of spatial self-organization in the design of agroforestry systems. PLoS One 15(7):e0236325

Vetaas VR (1992) Micro-site effects of trees and shrubs in dry savannas. J Veg Sci 3:337–344

Weltzin JF, Coughenour MB (1990) Savanna tree influence on understory vegetation and soil nutrients in North-Western Kenya. J Veg Sci 1:325–334

Wilson B (2002) Influence of scattered paddock trees on surface soil properties: a study of the northern tablelands of NSW. Ecol Manage Restor 3:211–219

Wilson B, Lemon J (2004) Scattered native trees and soil heterogeneity in grazing land on the Northern Tablelands of NSW. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, 5–9 December 2004, University of Sydney, Australia

Wu H, Sharpe PJH, Walker J, Penridge LK (1985) Ecological field theory: a spatial analysis of resource interference among plants. Ecol Model 29:215–243

Yadav JP, Sharma KK, Khanna P (1993) Effect of *Acacia nilotica* on mustard crop. Agr Syst 21: 91–98

Yadessa A, Itanna F, Olsson M (2009) Scattered trees as modifiers of agricultural landscapes: the role of *waddeessa* (*Cordia africana* lam.) trees in Bako area, Oromia, Ethiopia. Afr J Ecol 47: 78–83

Zinke PJ (1962) The pattern of influence of individual forest trees on soil properties. Ecology 43: 130–133

Chapter 22
Integrating *Moringa oleifera* and *Moringa stenopetala* in Agroforestry for Adaptation and Mitigation of Climate Change in Asia and Africa

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Abstract *Moringa oleifera* Lam. and *Moringa stenopetala* (Baker f.) Cufod. are popularly known as miracle trees because of their manifold benefits. *M. oleifera* is a widely distributed species and is being cultivated in many tropical and subtropical Asian countries. Compared to *M. oleifera*, *M. stenopetala* is mainly confined to East Africa. The *Moringa* tree is mainly cultivated for its high nutritional value and has tremendous potential to combat malnutrition. The two species are also valuable medicinal plants and widely used in traditional medicine. In this review, we provide a synthesis of the state of knowledge on the traditional uses and importance of *M. oleifera* and *M. stenopetala*, their nutritional and medicinal value, and other uses. We propose integration of these species in site-specific agroforestry systems to advance food and nutritional security while providing adaptation and mitigation benefits.

Keywords *Moringa* tree · East Africa · Asia · Nutritional security · Soil health

22.1 Introduction

Solving the problems of food and nutritional security requires a range of interconnected agricultural interventions, including improvements in staple crop productivity, the biofortification of staples, and the cultivation of a broader range of edible plants that provide fruits, nuts, and vegetables for more diverse diets (Frison et al. 2011). Some trees, especially fruit-bearing ones, have been managed

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by people for millennia, resulting in complex agroforestry systems (Clement et al. 2004). A combination of indigenous and exotic tree foods in agroforestry systems can supports nutrition, the stability of production, and farmers' incomes.

Moringa species is widely grown in Asia and Africa, and the tree has gained popularity because of its various multipurpose uses. *Moringa* species are particularly important as human food because almost every part of the trees is edible and for their very high nutritional values. In addition, both *M. oleifera* and *M. stenopetala* are known for their medicinal properties. Several studies (Mekonnen and Gessesse 1998; Katayon et al. 2006; Subramanium et al. 2011; Ullah et al. 2015; Thapa et al. 2019) have been carried out to assess the potential uses of the *Moringa* species. However, most of these studies have mainly focused on their nutritional values, chemical composition and medicinal and antimicrobial properties. Information is limited on their role in climate change adaptation, mitigation and other environmental management challenges. This chapter aims to provide a synthesis of the state of knowledge on the diversity, distribution, traditional uses, and their role in food security, land reclamation and climate change adaptation and mitigation potential of *M. oleifera* and *M. stenopetala*.

22.2 Scope of Review and Literature Search

This review aimed to systematically examine and summarize the range and nature of the literature on the potential and actual uses of *M. oleifera* and *M. stenopetala*. We selected *M. oleifera* and *M. stenopetala* for this review because of their multipurpose utility. A literature survey was carried out to document the various uses of these multipurpose trees. Journal articles, book chapters and scientific reports were identified through a comprehensive literature search carried out using Google scholar, web of science and individual journal databases using a combination of keywords. The key words included "*Moringa* tree," "*Moringa oleifera,*" "*Moringa stenopetala,*" "drumstick," "miracle tree," "antimicrobial activity," "socioeconomic," "sustainable agriculture," "medicinal properties," "soil health," "growth promoter," "bioenergy," and "biofertilizer." We screened a total of 350 research articles, out of which 71 articles were included in this study. We included studies that attempted to evaluate the different properties of *M. oleifera* and *M. stenopetala* such as nutritional values, medicinal properties, soil health improvement and natural phytohormone, water treatment, biofuel production, animal feed, climate change mitigation, and socioeconomic development, and articles other than this were excluded. The literature searched was limited to articles published in the English language without time limitations.

22.3 Synthesis

22.3.1 Distribution and Occurrence in Agroforestry

M. oleifera and *M. stenopetala* are among the 13 identified species of the monogeneric family Moringaceae, and are among the four edible species of the family (Olson 2017). A *Moringa* tree is a fast-growing, drought-resistant, deciduous, dicotyledonous tree that can reach a height of 5–10 m. *M. oleifera* can grow well in the humid tropics and hot, dry lands (Thapa et al. 2019), and it can endure a range of rainfall regimes from 250 mm to 3000 mm and a pH of 5–9 (Palada and Chang 2003). This species can be found at elevations of 0–1000 masl, and adapted to a wide range of soil types (Orwa et al. 2009). The tree has a soft trunk, gummy bark, and tripinnately compound leaf (Farooq et al. 2012). *M. stenopetala* is a strongly branched tree with a thick base with white to pale gray or silvery bark. Its trunk can grow up to 60 cm in diameter at its breast, and the tree has smooth wood and soft leaves (Jahn 1991). Whereas the *M. stenopetala* is native to East Africa and the species is mainly confined to its center of origin (Mataka et al. 2006). In Africa, *M. stenopetala* naturally grows in the *Acacia tortilis*-*Delonix elata*-*Commiphora* spp. vegetation-complex and can be found at the altitude of 400–2100 m. *M. stenopetala* does not have any specific soil requirement for its growth (Orwa et al. 2009). *M. stenopetala* is popularly known as "African *Moringa*" or "cabbage tree," but in parts of Ethiopia, the species is locally known as Kalanki and Haleko (Mataka et al. 2006). This species is an integral parts of traditional dryland agroforestry practices, where it occurs mostly as scattered trees on crop land or as components of home gardens (Jiru et al. 2006; Shode and Amanuel 2016; Taye and Tesfaye 2021).

M. oleifera is native to the Indian subcontinent. Nevertheless, later in the nineteenth century, the species was introduced into America. It is also widely cultivated in many countries like the Philippines, Cambodia, and the Caribbean Island (Velázquez-Zavala et al. 2016). *M. oleifera* is commonly known as "drumstick tree" or horseradish tree. The plant is also known by various names in different parts of the globe, such as in Ethiopia it is known as Shiferaw, as Shajmah or Sonjana in India and Sahijan or Sajan in Nepal (Thapa et al. 2019). *M. oleifera* is often grown in agroforestry arrangements as components of home gardens (Abbassy et al. 2020; Devkota and Bhusal 2020; Kumar et al. 2017; Vijaykumar et al. 2021). Moringa-based agroforestry systems are practiced in several Asian and African countries. Some cereal crops, like rice and wheat, as well as vegetables (mung bean and potatoes) are produced in Moringa-based agroforestry systems in Asian nations such as in India (Rathore et al. 2020; Vijaykumar et al. 2021). Similarly, in several African countries namely Nigeria and Niger, a variety of fruiting trees, grains, henna, soybean, cassava, and vegetables such as tomatoes, eggplant, and cabbages are found to be growing in Moringa-based agroforestry systems (Younoussou et al. 2016; Abdullahi and Anyaegbu 2017; Abdoul-Salam et al. 2021).

22.3.2 Food and Nutritional Values

Almost every part of the *Moringa* tree is edible including leaves, flowers, immature pods, and roots. Leaves of *Moringa* can be consumed as fresh, cooked, or stored as dried powder for many months without losing their nutritional value. Some tribes such as Gofa, Konso, Burji, and Gamo in Ethiopia consume fresh leaves of *Moringa* as vegetables, especially during the dry seasons (Raghavendra et al. 2016). In many parts of Ethiopia, the leaves of *M. stenopetala* are consumed like spinach with cereal balls and cabbage (Seifu 2015). In India and Bangladesh, flowers and flower buds with tender leaves of *M. oleifera* are consumed as leafy vegetables and prepared with green peas and potatoes. In the Northern part of India, very young pods are consumed as vegetables, and the tender pods garnished with mustard seed paste are cooked like beans and consumed with rice (Pandey et al. 2011).

M. oleifera and *M. stenopetala* trees contain many essential minerals like Ca, P, Na, K, Mg, Mn, Co, Cu, Fe, and Zn (Table 22.1). *Moringa* is also rich in vitamin A, vitamin B1, vitamin B2, vitamin B3, vitamin C, vitamin E, carbohydrate, protein, fats, crude fiber, beta-carotene, antioxidants, anti-inflammatory nutrients, and omega-3 and omega-6 fatty acids (Thapa et al. 2019). Leaves of these trees also contain essential amino acids like Arginine, Cysteine, Isoleucine, Leucine, Methionine, Phenylalanine, Threonine, and Valine (Table 22.2). The parts of the *Moringa* tree can provide more nutrients than many other nutritional plants. Gram-to-gram comparison of *M. oleifera* leaves with other healthy plants sources revealed that the leaves of the *Moringa* tree could provide seven times more vitamin C than oranges, ten times vitamin A found in carrots, 17 times the calcium found in milk, nine times protein found in yoghurt, 15 times potassium found in bananas and 25 times the iron found in spinach (Gopalakrishnan et al. 2016). However, the chemical composition of green pods and leaves of *M. stenopetala* and *M. oleifera* changes with season and elevation (Melesse et al. 2012). *M. oleifera* and *M. stenopetala* have almost all essential nutrients and supplements, for which many developing nations have used these species to combat malnutrition and enhance the food security of a country.

22.3.3 Medicinal Value

The *Moringa* tree has a significant contribution to the traditional medicine in Asia and Africa. Almost every part of the *Moringa* tree is considered to have medicinal properties. Different parts of the tree are used to treat ascites, rheumatism and venomous bites, and cardiac and circulatory stimulant (Sayeed et al. 2012). In many Indian states, leaves of *M. oleifera* are used to cure hallucination, dry tumors, hiccups, and asthma (Metha and Aggarawal 2008). Whereas the roots, barks, flowers, and seed oil help cure heart complaints, eye diseases, inflammation, dyspepsia, enlargement of spleen, muscle diseases, and leprous ulcers (Sayeed et al. 2012). In Ethiopia, the leaves and roots of *M. stenopetala* are used to cure malaria,

Table 22.1 Mineral contents of morphological fractions of *Moringa oleifera* and *M. stenopetala*

Elements	*M. oleifera*				*M. stenopetala*				Requirements[a]
	Leaves	Twigs	Pods	Whole forage	Leaves	Twigs	Pods	Whole forage	
g kg^{-1} DM									
Ca	12.9	6.5	17	22.5	12.1	2.3	18.8	16	1.9–8.2
P	6.2	8.1	4.8	6.5	3	4.6	4.9	4.5	1.2–4.8
Na	0.2	0.43	0.6	0.5	0.6	0.5	2.4	1.5	0.8–1.8
K	18.8	19.8	32.3	23.2	30.7	26.1	18.1	21.6	5–10
Mg	1.8	3	3.3	2.9	2.8	1.3	3.3	3.3	1.0–2.5
mg kg^{-1} DM									
Mn	91.1	33.2	79.1	102.9	33.7	23.4	44.7	49	20–40
Co	104	62.3	68.4	55.1	86.7	62.6	26.4	66.2	0.1–0.2
Cu	17.7	12.1	20.4	18.6	12.6	12.5	12.7	13.9	7–11
Fe	390.9	237.1	440	974.9	681.2	384.6	436.1	744.4	30–50
Zn	28.2	27.5	35.9	34	22.7	21.7	26.4	25.3	20–40

Source: Debela and Tolera (2013)
[a]Recommended mineral requirements for all classes of ruminants

Table 22.2 The concentration of essential amino acids in leaves of *Moringa oleifera* and *M. stenopetala* (g kg^{-1} DM)

Amino acids	*M. oleifera*	*M. stenopetala*
Arginine	15.4	13.1
Cysteine	3.55	3.91
Isoleucine	10.9	9.41
Leucine	21.4	18.6
Lysine	13.2	12.2
Methionine	4.24	3.65
Phenylalanine	16.4	13.7
Threonine	13	11.4
Valine	14	12

Source: (Melesse 2011)

hypertension, stomach problem, the expulsion of retained placenta, asthma, diabetes, common cold, and wound healing (Mekonnen and Gessesse 1998).

Studies have suggested that *Moringa* seeds contain proteins like lectin, 2S albumin, mMo-CBP_3–1, which show antifungal and antibacterial activities (Ullah et al. 2015). Various workers have carried out studies on different parts of *M. oleifera* and *M. stenopetala* to understand their antimicrobial activities against bacteria such as *Escherichia coli, Pseudomonas aeruginosa, Staphylococcus boydii, S. aureus*, and *S. pneumoniae* using different extraction methods (Table 22.3). These studies indicated that their seeds, leaves, flowers, and bark show antimicrobial activities against various microbes, which causes several diseases to human health. Recent studies have also shown the potential of *M. oleifera* as an immune booster against COVID 19 (Fajri 2021).

22.3.4 Moringa for Water Treatment

The use of chemicals for water treatment is a costly approach and is not available locally in many developing countries (Abd El-Hack et al. 2018). Thus, the use of natural coagulants to treat wastewater is gaining interest among researchers, and *M. oleifera* and *M. stenopetala* have been widely studied for clarification of turbid water (Abiyu et al. 2018). The seeds of *Moringa* contain some proteins that act as effective coagulants similar to those of alum and synthetic cationic polymers used for water and wastewater treatment, and it also provides coagulation effect at a low cost and low risk to humans and the environment (Abiyu et al. 2018; Dalvand et al. 2016).

Comparison of *M. oleifera* with other natural coagulants such as *Arachis hypogaea*, *Vigna unguiculata*, *Vigna mungo,* and *Zea mays* revealed that *M. oleifera* has better potential in removing the water turbidity than these natural coagulants (Subramanium et al. 2011). The study conducted in the rivers of African countries indicates reducing the water turbidity and color up to 90% and shows

Table 22.3 Antibacterial and antifungal activities of *Moringa oleifera* and *M. stenopetala* on various selected microbial strains

Source	*Moringa* species	Extract	Microbes	Main findings
Pal et al. (1995)	*M. oleifera*	Ethanolic extract of leaves	*Bacillus cereus, Bacillus subtilis, Staphylococcus aureus, Sarcina lutea*, *Escherichia coli* and acid-fast *Mycobacterium phlei*	Ethanolic extract shows antimicrobial activity against all selected strains of Gram-positive and Gram-negative bacteria
Nepolean et al. (2009)	*M. oleifera*	Aqueous and ethanolic extract of leaves, flower, and seed	*E. coli, K. pneumoniae, Enterobacter, P. aeruginosa, S. aureus*, and *Staphylococcus*	The parts of MO showed the highest antimicrobial activity in ethanolic extract than aqueous extract against organisms
Sahilu (2010)	*M. stenopetala*	Crude water extract of seeds	*E. coli, P. aeruginosa, S. boydii, S. aureus*, and *S. pneumoniae*	The crude water extract of seeds of *MS* has shown antimicrobial activity against all selected microbes
Thilza et al. (2010)	*M. oleifera*	Water extract of leaf	*Pseudomonas aeruginosa, Staphylococcus albus, S. aureus, Escherichia coli, S. pyogenes, Enterobacter aerogenes*	Water extract of *M. oleifera* leaves possesses some degree of antimicrobial activities, especially with high doses
Walter et al. (2011)	*M. stenopetala* and *M. oleifera*	Methanol and n-hexane extract of seeds	*Salmonella typhi*, *Escherichia coli*, and *Vibrio cholerae*	For methanol extract, the highest inhibitions were observed on *E. coli, S. typhi*, and *V. cholerae*, respectively, while for n-hexane extract, a higher inhibition was on *S. typhi* than on *V. cholerae* and *E. coli*

(continued)

Table 22.3 (continued)

Source	*Moringa* species	Extract	Microbes	Main findings
Saadabi and Zaid (2011)	*M. oleifera*	Aqueous and methanol extract of seeds	*Staphylococcus aureus*, *Bacillus subtilis*, *E. coli, Pseudomonas aeruginosa, Aspergillus niger, Candida albicans*	Aqueous and methanol extracts have a substantial inhibitory effect against the four tested bacterial strains. The aqueous solution was superior in suppressing bacterial and fungal growth. However, there was no detectable suppression in the growth of *C. albicans* in both aqueous and methanol extract
Raj et al. (2011)	*M. oleifera*	Petroleum ether, ethyl acetate, chloroform, ethanol, and aqueous extract of the root	*Escherichia coli, Staphylococcus aureus*, *Pseudomonas aeruginosa, Proteus mirabilis*, *Penicillium* sp., *Mucor* sp., *Aspergillus niger,* and *Candida albicans*	Ethyl acetate extract showed high antibacterial activity against *P. aeruginosa*, and chloroform extract was ineffective against *E. coli* and *P. mirabilis*. Aqueous extract showed maximum inhibition against *Penicillium* sp. compared to other extracts, and *A. niger* were ineffective in all the extracts except aqueous extract
Patel et al. (2014)	*M. oleifera*	Water and ethanol extract of leaf	*S. cerevisiae, C. albicans, C. tropicalis*	The largest zone of inhibition was produced by water and ethanol extract of *M. oleifera* against *S. cerevisiae*
Chekesa and Mekonnen (2015)	*M. stenopetala*	Leaves, stem bark, root bark, and seed extracts of methanol, ethyl acetate, and chloroform	*S. aureus, P. aeruginosa, E. coli,* and *S. boydii*	80% of the crude extract of seed has the highest antimicrobial activity against *S. aureus,* and the chloroform

(continued)

Table 22.3 (continued)

Source	*Moringa* species	Extract	Microbes	Main findings
				fractions of seed have the best anti-microbial activity against all the selected bacterial strains
Hagos et al. (2018)	*M. stenopetala*	Methanolic and aqueous extract of leaves	*E. coli, P. vulgaris, P. aeruginosa, S. aureus, S. faecalis*	Methanolic extract of leaves shows the most promising broad-spectrum antibacterial activities against both Gram-positive and Gram-negative bacteria
Seleshe and Kang (2019)	*M. stenopetala*	Chloroform, methanol, ethanol, and water extract of leaves	*K. pneumoniae, B. cereus, S. pneumoniae, S. aureus, L. monocytogenes, E. coli, S. typhimurium, C. albicans,* and *A. niger*	*M. stenopetala* leaves have great potential in the development of food preservatives and antibiotic drugs

efficiency in controlling or reducing microbial growth up to 95% (Nkurunziza et al. 2009). Several studies also revealed that both species have an effective coagulation property, which can remove the water turbidity by 70–97% (Katayon et al. 2006; Megersa et al. 2019). Water pH is an essential factor in determining coagulation capacity and *Moringa* seed powder gives a better result in the pH range between 6.5 and 9, while alkaline conditions are better for clarification (Thakur and Choubey 2014).

Studies on heavy metals removal from wastewater show that the seed extract of the *Moringa* tree can successfully eliminate heavy metals like Fe, Cu, Pb, Cd, Cr, and Zn up to 98% (Mataka et al. 2006). However, comparing *M. oleifera* and *M. stenopetala* in lead removal from water, *M. stenopetala* showed a better result in Pb detoxification over *M. oleifera* (Mataka et al. 2006). In addition, *M. oleifera* and *M. stenopetala* seed extract also have the potential to eliminate dyes such as Carmine Indigo, Chicago Sky Blue 6B, Direct Red 23 azo dyes up to 80–90% and other chemicals released from various textiles and pharmaceutical industries (Beltrán-Heredia et al. 2009; Beltrán-Heredia and Sánchez 2008; Dalvand et al. 2016).

22.3.5 Agricultural Use

22.3.5.1 Growth Hormones and Crop Production

M. oleifera leaves contain five different growth hormones (auxins, gibberellins, abscisic acid, ethylene, and cytokinins) and several mineral elements (i.e., P, Ca, Mg, Fe, Cu, Zn, and Mn), which can be utilized as a natural plant growth promoters to enhance food production (Howladar 2014). Hanafy (2017) reported that the spraying of *Moringa* leaf extract can alter the effect of drought on the *Glycine max* plants resulting in significant growth in shoot and root length and dry weight, and chlorophyll pigments. Spraying of *M. oleifera* leaf extract with organo-biodegradable fertilizer on sweet bell pepper (*Capsicum annum*) influenced plant height, leaf number, fruit weight, and fruit number (Dunsin and Odeghe 2015). In addition, studies have revealed that applying *M. oleifera* and *M. stenopetala* leaf extract as natural phytohormone at different concentrations can improve yields in several crops such as maize, cherry tomatoes, wheat, pea, maize, tomatoes, piper, and common beans (Table 22.4). In comparison, very few studies have been reported with *M. stenopetala* as a natural phytohormone than *M. oleifera* to improve crop yield and further invention is needed to see the potential of *M. stenopetala* in crop improvement.

22.3.5.2 Green Manure and Soil Health Improvement

Green manures are believed to be the alternative to chemical fertilizers as they are cheaper than chemical fertilizers and environmentally friendly. However, the effect of green manure on crop production and soil properties depends on its chemical composition. Agbede (2018) reported that the application of *M. oleifera* as green manure could be beneficial for agricultural land, as it reduces the soil bulk density, increases soil organic matter (OM) with P, K, Ca, and Mg.

As such, the cultivation of *M. stenopetala* tree can significantly improve soil health by improving soil organic carbon, organic matter, nitrogen content, and maintaining soil pH (Fig. 22.1a–d), and it upgrades the soil capacity to supply plant nutrients and help a sustainable ecosystem (Abay et al. 2015).

22.3.6 Animal Feed

The *Moringa* trees can also be used as fodder when the quality and quantity of other forages is limited (Debela and Tolera 2013). As a nutrient source supplement to forage, *Moringa* leaf meal can improve the growth performance and milk production in goats and cows. *Moringa* leaves can also be used at 5–20% in poultry diets (Üstündağ and Özdoğan 2016). Inclusion of *Moringa* leaves in goat diet at

Table 22.4 Effects of *M. oleifera* and *M. stenopetala* leaves extract as natural phytohormone on different crop plants and crop yield

Author	*Moringa* sp.	Crop sp.	Effects of *Moringa* leave extract on crop plant	Improvement in crop yield (%)
Mishra et al. (2013)	*M. oleifera*	Pea (*Pisum sativum*)	Increment in fresh and dry weight of pea pods	51.84
Mvumi et al. (2013)	*M. oleifera*	Common beans (*Phaseolus vulgaris*)	Spraying *Moringa* leave extract increases the dry weight of beans, root weight and plant height	166.66
Mvumi et al. (2013)	*M. oleifera*	Maize (*Zea mays*)	*Moringa* extract has no significant effect on dry matter, root weight and crop height in greenhouse	128.57
Basra and Lovatt (2016)	*M. oleifera*	Cherry tomatoes (*Solanum lycopersicum*)	Increased in the number of lateral floral shoots produced per cherry tomato plant, increased final canopy biomass	36.55
Biswas et al. (2016)	*M. oleifera*	Maize (*Zea mays*)	Increased the growth parameters like plant height, shoot length, fresh and dry weight of shoot, and yield component	46.03
Matthew (2016)	*M. oleifera*	Pepper (*Capsicum annum*)	Produce greater stem girth, a higher number of leaves, and a higher fruit number	64.12
Jhilik et al. (2017)	*M. oleifera*	Wheat (*Triticum aestivum*)	Produced tall plants, fresh weight and dry weight of root and shoot increased, produced a high number of spikelets spike and filled grain spike	20.99
Hoque et al. (2020)	*M. oleifera*	Cabbage (*Brassica oleracea*)	MLE increases the plant height, leaf number, leaf length, and leaf weight	42.6
Azene et al. (2021)	*M. stenopetala*	Maize (*Zea mays*)	MLE significantly increases the leaf length, leaf area, stem thickness	9.06

20–50% could help increase the live-weight and digestibility of dry matter, crude protein, and organic matter (Aregheore 2002), and dietary *Moringa* leave extract could enhance milk yield by 6% (Kholif et al. 2019). Similarly, like animals, adequate levels of dietary *Moringa* leaves in poultry could have significant effects on growth, production, performance and carcass characteristics of birds. It has been reported that better feed efficiency could be a result of improved digestibility and antimicrobial properties against gut pathogens (Ayssiwede et al. 2011), and diets containing 5% of *Moringa* leaves can increase the weight of broiler chickens (Safa and El-Tazi 2012; El-Tazi 2014).

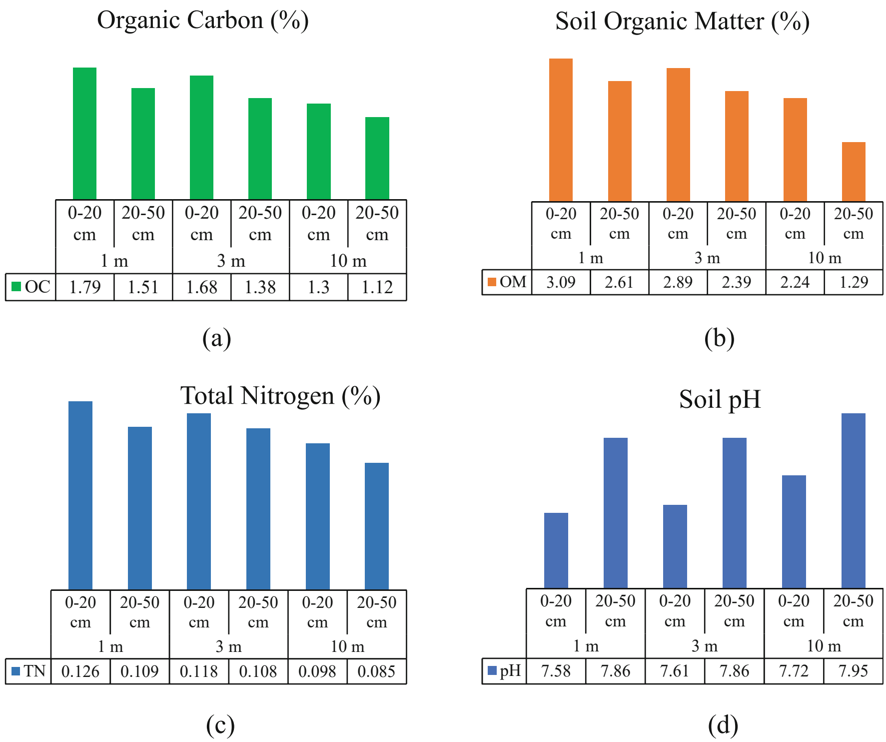

Fig. 22.1 (**a**) Organic carbon concentration at different depth and different distance from the cultivation. (**b**) SOM concentration at different depth and different distance from the cultivation. (**c**) TN concentration at different depth and different distance from the cultivation. (**d**) pH at defferent depth and different distance from the cultivation

22.3.7 Climate Change Mitigation

Moringa tree could play a crucial role in mitigating climate change effects through their potential for biofuel production and carbon sequestration.

22.3.7.1 Potential of Biofuel Production

As the global fossil reserve constantly decreases, biodiesel is gaining popularity among researchers as an alternative energy source. Furthermore, biofuel utilization such as biodiesel signifies clean, renewable, and sustainable alternatives to petroleum-based conventional diesel fuel. Studies revealed that the seeds of *M. oleifera* and *M. stenopetala* contain about 45% of oil and about 73–76% of

Table 22.5 Fuel properties of *MO* methyl extract and *MS* methyl esters and the mixture of methyl and ethyl ester compared with fossil diesel and ASTM standards and EN 14214

Fuel property	MOME	MSME	MSME/EE	Fossil diesel	ASTM D6751	EN 14214
Density at 15 °C (kg/ms)	875	885	887.2	820–860	–	860–900
Viscosity at 40 °C (cSt)	4.8	4.58	4.69	2.0–4.5	1.9–6.0	3.5–5
Calorific value (MJ/kg)	43.28	38.23	39.5	44.8	–	–
Cetane number	67	–	–	46	Min 47	Min 51
Flash point (°C)	162	185	197	60–80	Min 120	Min 130
Pour point (°C)	17	12	12	−35 to −15	–	–
Cloud point (°C)	17	15	15	−15 to 5	–	–
Ash content % (m/m)	0.01	0.0098	0.0067	100 max.	0.01	–
Lubricity HFRR; um	139	–	–	0.460 mm	–	–

MOME M. oleifera methyl esters, *MSME M. stenopetala* methyl ester, *MSME/EE M. stenopetala* methyl and ethyl ester
Source: Ivase (2018) and Ejigu et al. (2010)

oleic acid. In addition, seeds of *M. stenopetala* also contain 78% of mono-saturated fatty acids and 22% saturated acids (Ejigu et al. 2010), and a low amount of polyunsaturated fatty acid (<1%) was found in the seeds of *M. oleifera* (Ayerza 2012). Biodiesel derived from *Moringa* seed oil has a high cetane number and is a new promising feedstock for biodiesel production (Ivase et al. 2015). *Moringa*-derived biodiesel has a higher flashpoint (162–197 °C), a beneficial safety feature, as this biodiesel can store at room temperature. *M. oleifera* and *M. stenopetala* methyl ester and methyl and ethyl ester mixture derived biodiesel complied with American standards ASTM D6751 and European standard EN 14214 (Table 22.5) and could be an acceptable substitute for petrodiesel.

22.3.7.2 Potential for Carbon Sequestration

Moringa tree produces heavy flushes, which could be a good sink for CO_2 absorption and utilization (Daba 2016). According to Chauhan et al. (2021), 16–20 years old *M. stenopetala* trees could sequester on an average 42.3 kg of carbon and can fix 8.6 kg of CO_2 tree^{-1} year^{-1}. A similar study by Suryawanshi et al. (2014) found that the *M. oleifera* tree has potential to sequester about 15.7 ton of carbon tree^{-1}. A comparative study of the *M. oleifera* tree with a Japanese cedar tree shows that the *Moringa* tree can absorb about 20 times more carbon than the cedar tree (Daba 2016). Because of their natural capacity to improve the environment, integration of *Moringa* trees in an agroforestry system could mitigate the impact of climate change.

22.4 Efforts to Popularize Moringa in Agroforestry

Many international organizations, NGOs and government institutions are making efforts to popularize and scale up its planting in agroforestry. Some of the international initiatives such as the Moringa fund, Trees for Life, Moringa Network, Moringa initiatives, and Moringa news have been established to improve production of *Moringa* specially for human nutrition (Gandji et al. 2018). Since the 1990s, the Food and Agriculture Organization (FAO) is promoting *Moringa* in participatory agroforestry program and more recently as an intercropping species in post-Haiyan recovery in the Philippines and in a collaborative food and nutrition program in the SNNPR region in Ethiopia. In 2014, the Swiss government funded a research project with an objective of enhancing livelihood of rural communities while improving the environment services on farm land, through promotion of indigenous multipurpose trees *M. oleifera* in agroforestry systems. The Moringa fund which targets agroforestry projects, invested in Asante Capital EPZ (a sustainable agroforestry company) to develop Moringa based agroforestry system in Kenya. Similarly, Sustainable Bioresources, a Limited Liability Company (LLC), aimed to grow *Moringa* in Hawaii for improving food security. For that, in 2021, they provided free *Moringa* seedlings to farmers for intercropping it with *Pipturus albidus*, which is used for making tea and other high value beverage products.

Integration of *Moringa* tree in agroforestry system could diversify the distribution of the species and provide a substantial proportion of energy and nutritive requirement of the local diet (Rahman et al. 2013). *Moringa* based agroforestry such as *Moringa*-mung bean-potato could be one of the most productive agroforestry systems, which could produce goods up to 36.2 Mg ha^{-1} (Rathore et al. 2020). *Moringa* tree has been reported to have high economic and cultural values and many people around the globe are engaged with the distribution and sales of different parts of the *Moringa* tree. Cultivation of *M. oleifera* in a hectare of land could give farmers a gross income of 75,924 USD per year (Omotesho et al. 2013). In Ethiopia, the leaves of *M. stenopetala* are marketed as vegetables, and farmers earn on average 4022.2 Birr/year/household from the selling of different products of *M. stenopetala* (Abay et al. 2015). In western Nigeria, *Moringa* production gave an average net profit of 59.8% per hectare per year from the sale of leaves (Animashaun and Toye 2013).

The main challenges for integrating *Moringa* in agroforestry are the relatively long juvenile period, lack of planting materials (stem cuttings), the requirement of a greater number of rainy days in regions where water is scarce, and vulnerability to pests and diseases. To shorten the juvenile period, Horticultural College and Research Institute in Tamil Nadu Agricultural University (TNAU) has developed and released two improved varieties of annual *Moringa*, named PKM-1 and PKM-2 for commercial cultivation, which has revolutionized the *Moringa* cultivation in India. These varieties of *Moringa* flower within 5–6 months after sowing and come to harvest within 7–8 months, and can yield up to 52–98 Mg ha^{-1} (TNAU 2018).

22.5 Conclusions

Based on the review of the literature, it is concluded that *M. oleifera* and *M. stenopetala* trees have very high nutritional value which could be used to alleviate food insecurity and malnutrition in parts of Asia and Africa. It is also concluded that *Moringa* trees have several medicinal and antimicrobial properties. Besides, the role of *M. oleifera* and *M. stenopetala* in water treatment, biofuel production, agriculture, climate change mitigation and socioeconomic growth has also been established. Furthermore, *Moringa* tree can be a potential multipurpose crop to utilize marginal and degraded lands. However, compared to *M. oleifera,* little attention has been given to *M. stenopetala* and further research is needed to harness its full potential.

References

Abay A, Birhane E, Taddesse T, Hadgu KM (2015) *Moringa stenopetala* tree species improved selected soil properties and socio-economic benefits in Tigray, Northern Ethiopia. Sci Technol Arts Res J 4(2):68–78. https://doi.org/10.4314/star.v4i2.10

Abbassy M, Salem MZ, Rashad NM, Afify SM, Salem AZ (2020) Nutritive and biocidal properties of agroforestry trees of *Moringa oleifera* lam., *Cassia fistula* L., and *Ceratonia siliqua* L. as non-conventional edible vegetable oils. Agrofor Syst 94(4):1567–1579. https://doi.org/10.1007/s10457-018-0325-4

Abdoul-salam K, Massaoudou M, IKA R, Abass T, Zouberou AM (2021) *Moringa oleifera* based agroforestry system in carbon sequestration. J Innov Agric 8(3):17–24. https://doi.org/10.37446/jinagri/rsa/8.3.2021

Abdullahi IN, Anyaegbu PO (2017) The performance of soybean using Moringa as alley to improve soil productivity in north-Central Nigeria. Afr J Agric Res 12(14):1182–1189. https://doi.org/10.5897/AJAR2017.12128.17-24

Abiyu A, Yan D, Girma A, Song X, Wang H (2018) Wastewater treatment potential of *Moringa stenopetala* over *Moringa oleifera* as a natural coagulant, antimicrobial agent and heavy metal removals. Cogent Environ Sci 4(1):1433507. https://doi.org/10.1080/23311843.2018.1433507

Agbede TM (2018) Effect of green manure application on cassava (*Manihot esculenta* Crantz) growth, yield quantity and quality in degraded Alfisols. Pertanika J Trop Agric Sci 41(4): 1757–1777

Animashaun JO, Toye AA (2013) Feasibility analysis of leaf-based *Moringa oleifera* plantation in the Nigerian Guinea savannah: case study of University of Ilorin Moringa plantation. Agrosearch 13(3):218–231

Aregheore EM (2002) Intake and digestibility of *Moringa oleifera*–batiki grass mixtures by growing goats. Small Rumin Res 46(1):23–28. https://doi.org/10.1016/S0921-4488(02)00178-5

Ayerza R (2012) Seed and oil yields of *Moringa oleifera* variety Periyakalum-1 introduced for oil production in four ecosystems of South America. Ind Crop Prod 36(1):70–73. https://doi.org/10.1016/j.indcrop.2011.08.008

Ayssiwede SB, Dieng A, Bello H, Chrysostome CAAM, Hane MB, Mankor A, Dahouda M, Houinato MR, Hornick JL, Missohou A (2011) Effects of *Moringa oleifera* (lam.) leaves meal incorporation in diets on growth performances, carcass characteristics and economics results of growing indigenous Senegal chickens. Pak J Nutr 10(12):1132–1145

Azene A, Chauhan R, Tesfaye A, Misgana D (2021) Effect of leaf extract of some multipurpose trees and its concentrations on growth and production of maize. Trop Subtrop Agroecosyst 24(2) https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/3548

Basra SM, Lovatt CJ (2016) Exogenous applications of Moringa leaf extract and cytokinins improve plant growth, yield, and fruit quality of cherry tomato. Horticult Technol 26(3): 327–337. https://doi.org/10.21273/HORTTECH.26.3.327

Beltrán-Heredia J, Sánchez MJ (2008) Azo dye removal by *Moringa oleifera* seed extract coagulation. Color Technol 124(5):310–317. https://doi.org/10.1111/j.1478-4408.2008.00158.x

Beltrán-Heredia J, Sánchez-Martín J, Delgado-Regalado A (2009) Removal of carmine indigo dye with *Moringa oleifera* seed extract. Ind Eng Chem Res 48(14):6512–6520. https://doi.org/10.1021/ie9004833

Biswas AK, Hoque TS, Abedin MA (2016) Effects of Moringa leaf extract on growth and yield of maize. Prog Agric 27(2):136–143. https://doi.org/10.3329/pa.v27i2.29322

Chauhan R, Hailemariam T, Ugo Y, Shibru S, Anjulo A, Debella A, Misgana D (2021) Growth and carbon sequestration potential of Moringa (*Moringa stenopetala*) along an altitudinal gradient in southern Ethiopia. Trop Subtrop Agroecosyst 24(3):87

Chekesa B, Mekonnen Y (2015) Antibacterial activity of *Moringa stenopetala* against some human pathogenic bacterial strains. Sci Technol Arts Res J 4(2):190–198. https://doi.org/10.4314/star.v4i2.23

Clement CR, Weber JC, Van LJ, Domian CA, Cole DM, Lopez LA, Argüello H (2004) Why extensive research and development did not promote use of peach palm fruit in Latin America. Agrofor Syst 61(1):195–206. https://doi.org/10.1023/B:AGFO.0000028999.84655.17

Daba M (2016) Miracle tree: a review on multi-purposes of *Moringa oleifera* and its implication for climate change mitigation. J Earth Sci Clim Change 7(4). https://doi.org/10.4172/2157-7617.1000366

Dalvand A, Gholibegloo E, Ganjali MR, Golchinpoor N, Khazaei M, Kamani H, Hosseini SS, Mahvi AH (2016) Comparison of *Moringa stenopetala* seed extract as a clean coagulant with alum and *Moringa stenopetala*-alum hybrid coagulant to remove direct dye from textile wastewater. Environ Sci Pollut Res 23(16):16396–16405. https://doi.org/10.1007/s11356-016-6708-z

Debela E, Tolera A (2013) Nutritive value of botanical fractions of *Moringa oleifera* and *Moringa stenopetala* grown in the mid-Rift Valley of southern Ethiopia. Agrofor Syst 87(5):1147–1155. https://doi.org/10.1007/s10457-013-9626-9

Devkota S, Bhusal KK (2020) *Moringa oleifera*: a miracle multipurpose tree for agroforestry and climate change mitigation from the Himalayas—a review. Cogent Food Agric 6(1). https://doi.org/10.1080/23311932.2020.1805951

Dunsin O, Odeghe TO (2015) Response of sweet bell pepper to Moringa leaf extract and organo-bio degradable fertilizer. Asian J Agric Biol 3(4):117–123

Ejigu A, Asfaw A, Asfaw N, Licence P (2010) *Moringa stenopetala* seed oil as a potential feedstock for biodiesel production in Ethiopia. Green Chem 12(2):316–320. https://doi.org/10.1039/B916500B

El Tazi SM (2014) Effect of feeding different levels of *Moringa oleifera* leaf meal on the performance and carcass quality of broiler chicks. Int J Sci Res 3(5):147–151

El-Hack A, Mohamed E, Alagawany M, Elrys AS, Desoky ESM, Tolba H, Elnahal ASM, Elnesr SS, Swelum AA (2018) Effect of forage *Moringa oleifera* L. (Moringa) on animal health and nutrition and its beneficial applications in soil, plants and water purification. Agriculture 8(9): 145. https://doi.org/10.3390/agriculture8090145

Fajri M (2021) The potential of *Moringa oleifera* as immune booster against COVID 19. In: IOP Conference Series: Earth and Environmental Science, vol 807. IOP, Philadelphia, PA, p 022008

Farooq F, Rai M, Tiwari A, Khan AA, Farooq S (2012) Medicinal properties of *Moringa oleifera*: an overview of promising healer. J Med Plant Res 6(27):4368–4374. https://doi.org/10.5897/JMPR12.279

Frison EA, Cherfas J, Hodgkin T (2011) Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3(1):238–253. https://doi.org/10.3390/su3010238

Gandji K, Chadare FJ, Idohou R, Salako VK, Assogbadjo AE, Kakaï RG (2018) Status and utilisation of *Moringa oleifera* lam: a review. Afr Crop Sci J 26(1):137–156. https://doi.org/10.4314/acsj.v26i1.10

Gopalakrishnan L, Doriya K, Kumar DS (2016) *Moringa oleifera*: a review on nutritive importance and its medicinal application. Food Sci Human Wellness 5(2):49–56. https://doi.org/10.1016/j.fshw.2016.04.001

Hagos Z, Teka MZ, Brhane MY, Chaithanya KK, Gopalakrishnan VK, Weletnsae T (2018) In vitro antibacterial activities of the methanolic and aqueous extracts of *Moringa stenopetala* leaves. J Pharm Res 12(5):788

Hanafy R (2017) Using *Moringa oleifera* leaf extract as a bio-fertilizer for drought stress mitigation of Glycine max L. plants. Egypt J Bot 57(2):281–292. https://doi.org/10.21608/ejbo.2017.596.1027

Hoque TS, Rana MS, Zahan SA, Jahan I, Abedin MA (2020) Moringa leaf extract as a bio-stimulant on growth, yield and nutritional improvement in cabbage. Asian J Med Biol Res 6(2):196–203. https://doi.org/10.3329/ajmbr.v6i2.48050

Howladar SM (2014) A novel *Moringa oleifera* leaf extract can mitigate the stress effects of salinity and cadmium in bean (*Phaseolus vulgaris* L.) plants. Ecotoxicol Environ Saf 100:69–75. https://doi.org/10.1016/j.ecoenv.2013.11.022

Ivase TJP, Bobbo H, Tagago TA, Nyakuma DD (2015) A review of *Moringa oleifera* seed oil as feedstock for biodiesel production. J Multidiscip Eng Sci Technol 2(12):3574–3581

Jahn SAA (1991) The traditional domestication of a multipurpose tree *Moringa stenopetala* (Bak. F.) Cuf. In the Ethiopian Rift Valley. Ambio 20:244–247

Jhilik NZ, Hoque TS, Moslehuddin AZM, Abedin MA (2017) Effect of foliar application of Moringa leaf extract on growth and yield of late sown wheat. Asian J Med Biol Res 3(3):323–329. https://doi.org/10.3329/ajmbr.v3i3.34520

Jiru D, Sonder K, Alemayehu L, Mekonen Y, Anjulo A (2006) Leaf yield and nutritive value of *Moringa stenopetala* and *Moringa oleifera* accessions: its potential role in food security in constrained dry farming agroforestry system. In: Proceedings of the Moringa and other highly nutritious plant resources: strategies, standards and markets for a better impact on nutrition in Africa, Accra, Ghana, 16–18. https://www.oilseedcrops.org/wp-content/uploads/2012/11/Ethopia-Intercropping-Multi-Storey-garden.pdf

Katayon S, Noor MMM, Asma M, Ghani LA, Thamer AM, Azni I, Ahmad J, Khor BC, Suleyman AM (2006) Effects of storage conditions of *Moringa oleifera* seeds on its performance in coagulation. Bioresour Technol 97(13):1455–1460. https://doi.org/10.1016/j.biortech.2005.07.031

Kholif AE, Gouda GA, Galyean ML, Anele UY, Morsy TA (2019) Extract of *Moringa oleifera* leaves increases milk production and enhances milk fatty acid profile of Nubian goats. Agrofor Syst 93(5):1877–1886. https://doi.org/10.1007/s10457-018-0292-9

Kumar Y, Thakur TK, Sahu ML, Thakur A (2017) A multifunctional wonder tree: *Moringa oleifera* lam open new dimensions in field of agroforestry in India. Int J Curr Microbiol App Sci 6(8):229–235. https://doi.org/10.20546/ijcmas.2017.608.031

Mataka LM, Henry EMT, Masamba WRL, Sajidu SM (2006) Lead remediation of contaminated water using *Moringa stenopetala* and *Moringa oleifera* seed powder. Int J Environ Sci Technol 3(2):131–139. https://doi.org/10.1007/BF03325916

Matthew A (2016) Moringa leaf extract on the growth and yield of pepper (*Capsicum annuum* L.). ARPN. J Agric Biol Sci 11(3):107–109

Megersa M, Gach W, Beyene A, Ambelu A, Triest L (2019) Effect of salt solutions on coagulation performance of *Moringa stenopetala* and *Maerua subcordata* for turbid water treatment. Sep Purif Technol 221:319–324. https://doi.org/10.1016/j.seppur.2019.04.013

Mekonnen Y, Gessesse A (1998) Documentation on the uses of *Moringa stenopetala* and its possible antileishmanial and antifertility effects. SINET 21(2):287–295

Melesse A (2011) Comparative assessment on chemical compositions and feeding values of leaves of *Moringa stenopetala* and *Moringa oleifera* using in vitro gas production method. Ethiopian J Appl Sci Technol 2(2):31–41

Melesse A, Steingass H, Boguhn J, Schollenberger M, Rodehutscord M (2012) Effects of elevation and season on nutrient composition of leaves and green pods of *Moringa stenopetala* and *Moringa oleifera*. Agrofor Syst 86(3):505–518. https://doi.org/10.1007/s10457-012-9514-8

Metha A, Aggarawal B (2008) Antiasthmatic activity of *Moringa oleifera* lam. Indian J Pharm 40: 28–31

Mishra SP, Pankaj S, Sanjay S, Rameshwar D, Prasad RS (2013) *Moringa oleifera* leaf extract as bio-stimulant for increasing pea yield. Indian For 139(6):562–563

Mvumi C, Tagwira F, Chiteka AZ (2013) Effect of Moringa extract on growth and yield of maize and common beans. Greener J Agric Sci 3(1):2276–7770. https://doi.org/10.15580/GJAS.2013.1.111512264

Nepolean P, Anitha J, Emilin RR (2009) Isolation, analysis and identification of phytochemicals of antimicrobial activity of *Moringa oleifera* lam. Curr Biotica 3(1):33–37

Nkurunziza T, Nduwayezu JB, Banadda EN, Nhapi I (2009) The effect of turbidity levels and *Moringa oleifera* concentration on the effectiveness of coagulation in water treatment. Water Sci Technol 59(8):1551–1558. https://doi.org/10.2166/wst.2009.155

Olson ME (2017) Moringa frequently asked questions. In: Palada MC (ed) Proceedings of the International Symposium on Moringa, Manila, Philippines, 15-18 November 2015. International Society for Horticultural Science (ISHS), Leuven L, Belgium

Omotesho KF, Sola-Ojo FE, Fayeye TR, Babatunde RO, Otunola GA, Aliyu TH (2013) The potential of Moringa tree for poverty alleviation and rural development: review of evidences on usage and efficacy. Int J Dev Sustain 2(2):799–813

Orwa C, Mutua A, Kindt R, Jamnadass R, Anthony S (2009) Agroforestry Database: a tree reference and selection guide version 4.0. http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp

Pal SK, Mukherjee PK, Saha K, Pal M, Saha BP (1995) Antimicrobial action of the leaf extract of *Moringa oleifera* lam. Anc Sci Life 14(3):197

Palada MC, Chang LC (2003) Suggested cultural practices for Moringa. International cooperators' guide AVRDC. AVRDC pub, 03-545

Pandey A, Pradheep K, Gupta R, Nayar ER, Bhandari DC (2011) 'Drumstick tree' (*Moringa oleifera* lam.): a multipurpose potential species in India. Genet Resour Crop Evol 58(3): 453–460. https://doi.org/10.1007/s10722-010-9629-6

Patel P, Patel N, Patel D, Desai S, Meshram D (2014) Phytochemical analysis and antifungal activity of *Moringa oleifera*. Int J Pharm Pharm Sci 6(5):144–147

Raghavendra HL, Kekuda TP, Vijayananda BN, Duressa D, Solomon T (2016) Nutritive composition and antimicrobial activity of *Moringa stenopetala* (baker f.) Cufod. J Adv Med Pharmaceut Sci 10:1–9. https://doi.org/10.9734/JAMPS/2016/29987

Rahman SA, Baldauf C, Mollee EM, Abdullah-Al-PM, Abdullah-Al-Mamun M, Toy MM, Sunderland T (2013) Cultivated plants in the diversified homegardens of local communities in Ganges Valley, Bangladesh. Sci J Agric Res Manage 2013:1–6. http://www.sjpub.org/sjarm.html

Raj AJ, Gopalakrishnan VK, Yadav SA, Dorairaj S (2011) Antimicrobial activity of *Moringa oleifera* (lam.) root extract. J Pharm Res 4(5):1426–1427

Rathore SS, Shekhawat K, Singh VS, Babu SB, Singh RK, Upadhyay PK, Bhattacharyya R (2020) Diversified agroforestry systems improve carbon footprint and farmer's livelihood under limited irrigation conditions. bioRxiv. https://doi.org/10.1101/2020.07.17.208405

Saadabi AM, Zaid IA (2011) An in vitro antimicrobial activity of *Moringa oleifera* L. seed extracts against different groups of microorganisms. Aust J Basic Appl Sci 5(5):129–134

Safa MA, El-Tazi SM (2012) Effect of feeding different levels of Moringa oleifera leaf meal on the performance and carcass quality of broiler chicks. Int J Sci Res 3(5):2319–7064

Sahilu R (2010) Characterization and determination of fluoride removal efficiency and antimicrobial activities of *Moringa stenopetala* seeds. Master's thesis, Addis Ababa University, Addis Ababa, Ethiopia

Sayeed MA, Hossain MS, Chowdhury MEH, Haque M (2012) In vitro antimicrobial activity of methanolic extract of *Moringa oleifera* lam. fruits. J Pharmacogn Phytochem 1(4):94

Seifu E (2015) Actual and potential applications of *Moringa stenopetala*, underutilized indigenous vegetable of southern Ethiopia: a review. Int J Agric Food Res 3(4):8–19

Seleshe S, Kang SN (2019) In vitro antimicrobial activity of different solvent extracts from *Moringa stenopetala* leaves. Prev Nutr Food Sci 24(1):70. https://doi.org/10.3746/pnf.2019.24.1.70

Shode Y, Amanuel TW (2016) Financial analysis of moringa tree based agroforestry practice against mono-cropping system in Konso District (Woreda), southern Ethiopia. J Econ Sustain Dev 7:1–13

Subramanium S, Vikashni N, Matakite M et al (2011) Moringa oleifera and other local seeds in water purification in developing countries. Res J Chem Environ 15:135–138

Suryawanshi MN, Patel AR, Kale TS, Patil PR (2014) Carbon sequestration potential of tree species in the environment of North Maharashtra University Campus, Jalgaon (MS) India. Biosci Discov 5(2):175–179

Taye T, Tesfaye Y (2021) Role of *Moringa stenopetala* based agroforestry practice on rural household economy in Offa Woreda, southern Ethiopia. Int J Econ Energy Environ 6(2):29

Thakur SS, Choubey S (2014) Assessment of coagulation efficiency of *Moringa oleifera* and okra for treatment of turbid water. Arch Appl Sci Res 6(2):24–30

Thapa K, Poudel M, Adhikari P (2019) *Moringa oleifera*: a review article on nutritional properties and its prospect in the context of Nepal. Acta Sci Agric 3:47–54

Thilza IB, Sanni S, Zakari AI, Sanni FS, Muhammed T, Musa BJ (2010) In vitro antimicrobial activity of water extract of *Moringa oleifera* leaf stalk on bacteria normally implicated in eye diseases. Acad Arena 2(6):80–82

TNAU (2018) Crop improvement and varietal status of Moringa. In: Advances in production of Moringa, pp 1–8

Ullah A, Mariutti RB, Masood R, Caruso IP, Costa GHG, de Freita CM, Santos CR, Zanphorlin LM, Mutton MJR, Murakami MT, Arni RK (2015) Crystal structure of mature 2S albumin from *Moringa oleifera* seeds. Biochem Biophys Res Commun 468(1–2):365–371. https://doi.org/10.1016/j.bbrc.2015.10.087

Üstündağ AÖ, Özdoğan M (2016) Using *Moringa oleifera* in poultry nutrition. Magnesium 2700: 2998

Velázquez-Zavala M, Peón-Escalante IE, Zepeda-Bautista R, Jiménez-Arellanes MA (2016) Moringa (*Moringa oleifera* lam.): potential uses in agriculture, industry and medicine. Rev Chapingo Ser Hortic 22(2):95–116. https://doi.org/10.5154/r.rchsh.2015.07.018

Vijaykumar R, Mehera B, Khare N (2021) Performance of rice growth and yield under (*Moringa oleifera* L.) based agroforestry system with utilization of various types of manures. Population 9(8)

Walter A, Samuel W, Arama P, Joseph O (2011) Antibacterial activity of Moringa oleifera and Moringa stenopetala methanol and n-hexane seed extracts on bacteria implicated in water borne diseases. Afr J Microbiol Res 5(2):153–157

Younoussou R, Sitou L, Boubé M, Ali M (2016) Functional analysis of *Moringa oleifera* lam. Agroforestry systems in the valleys of the Niger river and Goulbi of Maradi (Niger). Asian J Appl Sci 4(4):844–856

Chapter 23
Payment for Ecosystem Services from Agroforestry: Case Studies and Lessons

Arun Jyoti Nath, Panna Chandra Nath, and Gudeta Weldesemayat Sileshi

Abstract The benefits obtained by the growing population from the local and global environment have been termed ecosystem services (ESs). Given the continuous degradation in environmental quality, different payment of ecosystem services (PES) has been employed to uplift the continuous life-supporting ESs. Multi-strata agroforestry is recognized globally for its numerous ESs, from cleaning air to soil enrichment to several provisioning services. Different case studies worldwide represented the successful applications of PES, specifically from Asia and Africa. Through this synthesis, we show that PES can be an excellent mechanism to incentivize farmers to preserve forest patches on their land through agroforestry interventions or converting degraded cropland into agroforestry systems. However, the application of PES in agroforestry has received little attention globally. Additionally, information about the on-the-ground application of PES from agroforestry is scanty. There are several social, economic, institutional and policy barriers to the widespread adoption of approaches and strategies to PES from agroforestry.

Keywords Payment of ecosystem services · Carbon stock · Exchange value

23.1 Introduction

Ecosystems services (ESs) are the benefits that humankind obtains from the ecosystems (Daily 1997; Jack et al. 2008). The ESs have been classified into four categories: provisioning, regulating, supporting and cultural (Capodagilo and Callegari 2018). From the local to the global level, the quality and quantity of ESs have reduced drastically in the last decades (MEA 2005). As a result, economic incentive-

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based programmes, which aim to preserve or restore ESs through financial incentives, have grown in popularity in the last two decades (Pirard 2012; GEF 2014; Ezzine-de-Blas et al. 2016). One such incentive-based mechanism is Payment for Environmental Services (PES), which relies on the principle that the beneficiary should be compensated for received ESs to service providers for their efforts (Pagiola and Platais 2002; Pagiola et al. 2008). PES is a market-based approach, where users of an environmental service pay the owners or managers of that service, conditional on changes in behaviours that are likely to affect the provision of the services (Wunder 2015). For example, PES may be conditional on commitments to protect or restore forest areas or sustainable forest management, such as management of forest fires (Jayachandran 2013; Jayachandran et al. 2017). Payments may also be tied to agricultural practices associated with reducing greenhouse gas (GHG) emissions or increasing carbon stocks.

Similarly, the introduction of agroforestry, improved tillage practices such as conservation agriculture and reduced use of fire in rangeland management (Garbach et al. 2012) are also considered for PES. Private markets could indulge in inducing environmental services when the benefits of services accrue to the management decision holders to produce crops and related products. However, a classic market failure occurring due to the externalities like population pressure initiated by the difference in social and private benefits could drastically impact the flow of ESs and result in a decline in the supply of the same (Heal 2000). Land use management practices could also have positive and negative impacts on ESs resulting from behavioural changes of the landowners or a whole community (Baral et al. 2014; Bhatta et al. 2014). For example, the agricultural practices of any upstream community could significantly alter the land use and management of downstream communities (Bhatta et al. 2014). To overcome such externalities, many governments have imposed control on the externalities in the form of regulations applying sanctions over the actors failing to comply with the mandates of the regulations (Jack et al. 2008).

PES is increasingly recognized for sustaining local livelihoods and natural environments (Hubermann 2009; Suich et al. 2017). Global dimensions of ESs were the trending factors further driving the scaling up of PES, such as increased willingness to pay for ESs, better relations and scale of economies helping reduce transaction and planning costs (Hubermann 2009; Strassburg et al. 2009; Kronenberg and Hubacek 2013). With over 550 on-going projects, PES has considerably increased in the recent decade, providing ensured benefits through programs called 'Exchange Value for Land Management Practices' (EVLMPs) (Salzman et al. 2018). Interestingly, PES is more attractive to landowners because they need to conserve their forests or agroforests to qualify for PES schemes (Jack and Jayachandran 2018). The REDD+ and CDMs afforestation projects with new international conservation initiatives could significantly generate a revenue chain for environmentally well-endowed developing countries (Kronenberg and Hubacek 2013). There is growing evidence that restoration efforts in degraded forests and cropland could succeed by implementing agroforestry interventions (Murniati et al. 2022). However, the role of PES in scaling up agroforestry for the restoration of degraded ecosystems and maintaining ESs is poorly understood due to a lack of comprehensive analysis and documentation. Therefore, this chapter aims to provide an up-to-date synthesis of the ESs provided by agroforestry practices and PES schemes focusing on Africa and Asia.

23.2 Ecosystem Services Provided by Agroforestry

Agroforestry provides several ESs and is increasingly recognized as multifunctional working land use for environmental and economic benefits (Jose 2009; Sileshi et al. 2007; Kuyah et al. 2019). With multifunctional strata integrated with trees, shrubs, herbs, understory vegetation, crops and/or animal has high potentials of the systems to enhance soil fertility, reduce erosion, improve water quality, increase biodiversity and sequester carbon (Garrett and McGraw 2000; Garrity 2004; Williams-Guillen et al. 2008; Jose 2009; Nair et al. 2009; Kuyah et al. 2019). The ESs provided by agroforestry practices accrue at different scales from local to global scales (Fig. 23.1), and these are briefly discussed in the following sections.

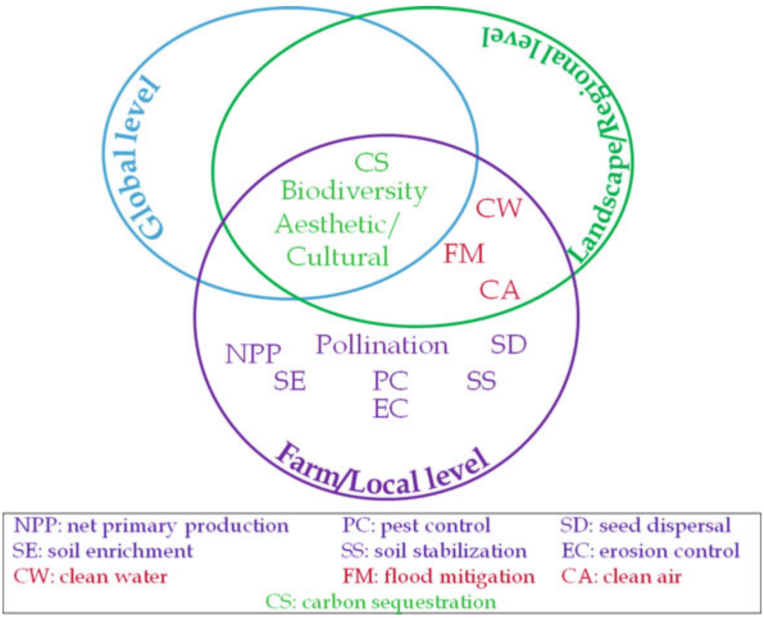

Fig. 23.1 Multifunctional benefits through ESs by agroforestry system at different scales (Jose 2009)

23.2.1 Provisioning Services

Provisioning services are the nutritional and non-nutritional materials obtained from ecosystems, including food, animal feed, energy, fibre, genetic resources and freshwater (Mafongoy and Sileshi 2020).

23.2.1.1 Food and Fodder Production

Agroforestry practices have been shown to increase food production through improved soil fertility, crop productivity (Sileshi et al. 2008, 2014), production of fruits, nuts, medicinal products (Akinnifesi et al. 2008a, b) and other saleable products.

The potential of agroforestry to increase the productivity of staple cereals such as maize and sorghum has been a subject of several reviews (Akinnifesi et al. 2010) and meta-analyses (e.g. Bayala et al. 2012; Kuyah et al. 2019; Sileshi et al. 2008, 2010). These analyses have established that crop yields were significantly increased under agroforestry compared to the control across different climates, elevations and soil types (e.g. Bayala et al. 2012; Kuyah et al. 2019; Sileshi et al. 2010). In addition, several reviews also show that fruit and nut-bearing trees in agroforestry systems are an essential source of food and medicinal products (Akinnifesi et al. 2008a, b; Jamnadass et al. 2011; Reang et al. 2021).

Agroforestry trees also provide fodder rich in proteins, vitamins and minerals. These trees have addressed forage scarcity in Africa and substitute dairy meals (Chakeredza et al. 2007; Paterson et al. 1998).

23.2.1.2 Fuelwood Production

In sub-Saharan Africa, the demand for fuelwood, agroprocessing, and charcoal continue to rise as the population increases. Agroprocessing operations such as tobacco curing require large quantities of fuelwood. For example, 9–37 and 19–33 m^3 of wood per ton of tobacco is required for flue and fire-cured tobacco in Tanzania (Geist 2000). Agroforestry practices can provide significant amounts of fuelwood. Studies have also shown that trees grown in contour strips, rotational woodlots, and fallows can produce large quantities of fuelwood (Sileshi et al. 2007). Field experiments in Zambia have revealed that improved fallows of *Sesbania* can produce up to 10 tonnes of wood per hectare within 2 years to meet household demand for fuel energy (Kwesiga and Coe 1994) and thus offer the potential to reduce the demand on forests for fuelwood.

23.2.1.3 Conservation of Biodiversity

Agroforestry practices are increasingly recognized as a pathway conserving tropical and temperate biodiversity (Schroth et al. 2004; McNeely 2004; Harvey et al. 2006). The system was influential because they provide habitat, warehouse of germplasm for essential species, reduce land-use change, connect corridors for sensitive habitats, and conserve biodiversity, thereby making continuity in the supply chain of different regulatory ESs (Jose 2009). Agroforestry practices also increase habitat heterogeneity with the composition of different species, minimal management and their land suitability (Harvey et al. 2006). The positive impact of agroforestry on the biodiversity conservation of nature reserves has been chiefly attributed to the reduced pressure on the natural forest due to the ability of agroforestry to sustain the livelihoods of local communities (Chirwa et al. 2008).

23.2.2 Regulating Services

Regulating services benefit from processes, including regulating climate control of floods and diseases. A large body of literature, including reviews and meta-analyses, has established that agroforestry practices can provide various regulating services (Kuyah et al. 2019; Muchane et al. 2020; Pumariño et al. 2015).

23.2.2.1 Soil Health

Nitrogen-fixing trees, now known as fertilizer trees, have been widely demonstrated to enrich soil productivity when integrated with crops (Sileshi et al. 2014). However, non-nitrogen fixing trees can also enhance soil health by maintaining the nutrient cycle in the soil in the tropics (Schroth and Sinclair 2003; Jose 2009). The published literature revealed agroforestry improves soil porosity while enhancing soil organic matter and biomass composed in microbial strata than any monoculture system (Lee and Jose 2003; Udawatta et al. 2008). An increase in soil organic matter significantly enhances soil health and water holding capacity and intercropped multidimensional trees in agroforestry systems also increase soil nutrient pool, thereby providing an additional check to soil erosion (Mishra 2011).

23.2.2.2 Carbon Sequestration

Agroforestry systems provide enhanced sink potential of atmospheric carbon in both above and below ground pools compared to other monoculture systems like crop or pasture (Luedeling et al. 2011; Muchane et al. 2020; Nath et al. 2021; Sharrow and Ismail 2004; Kirby and Potvin 2007). With the benefits of carbon credits, the most

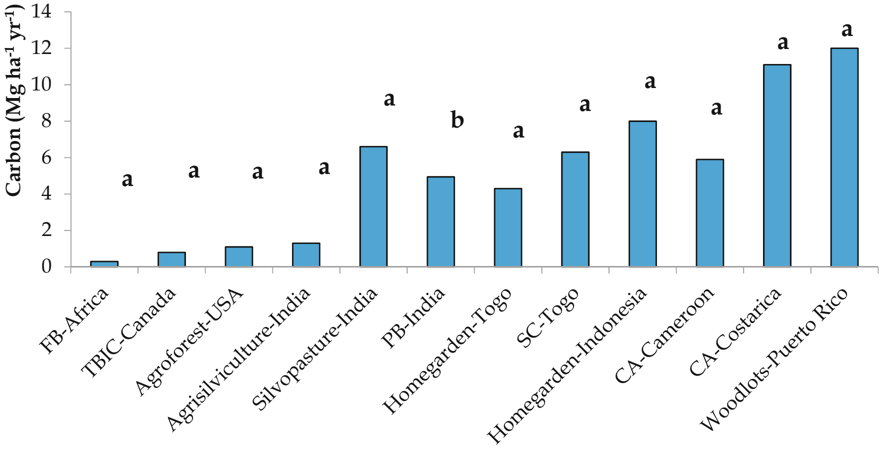

Fig. 23.2 Carbon sequestration potential of global agroforestry systems. *F.B.* fodder bank, *TBIC* tree-based intercropping, *P.B. Piper betle*, *SC* shaded coffee, *CA* Cacao agroforest. (*a*) Shreshta et al. (2018), (*b*) Brahma et al. (2018).

permanent form of carbon by rotating vegetation and further also serves to make durable products out of the harvested trees (Jose 2009). In a global assessment, Nair et al. (2009) estimated 1.02 billion ha of land under agroforestry systems potentially sequestered 1.1–2.2 Pg of carbon in five decades (Shreshta et al. 2018) which estimated to sequester 1.7×10^4 Mg additional carbon every year by 2040 with improved agroforestry management practices (IPCC 2000). However, the composition and age of the species, geographical location and management often determine the sink potential of the agroforestry systems. The carbon sequestration potential of different successful agroforestry systems across the world is given in Fig. 23.2.

23.2.2.3 Pest Control

Agroforestry practices have also been demonstrated to reduce insect pest and weed problems in cropping systems (Pumariño et al. 2015). For example, improved fallow species reduced termites and the parasitic weeds (*Striga* species) in maize crops in Zambia (Sileshi et al. 2005, 2006).

23.2.2.4 Microclimate Modification

Trees and shrubs in agroforestry systems can contribute to better microclimate by providing shade and windbreak, which are beneficial for livestock production and air and water quality. In addition, the introduction of buffer zones with agroforestry systems significantly reduces the negative impacts of dust, gas and microbial constituents (Tyndall and Colletti 2007; Jose 2009).

23.2.2.5 Groundwater Quality

They can also potentially increase groundwater quality by reducing the leaching impact of runoff caused by rainfall (Cassman 1999; Anderson et al. 2009). The deep rooting system of trees in the agroforestry system serves as a complex safety net controlling excessive nutrient loss to nearby aquatic bodies, mostly around the riparian zone and catchment areas (Jose 2009).

23.3 Theory and Practice of PES

Since its introduction in the 1970s, the concept of PES has been continuously broadened, and recently, socio-economic and conservation objectives have been merged with PES to further popularize it by MEA (2005) and by UNFCCC (COP21) (2015) to recognize its role in climate change (Capodagilo and Callegari 2018). PES schemes have also undergone rapid proliferation, and the introduction of PES in the Kyoto Protocol has given it an international platform (Fripp 2014).

Numerous co-services and materialistic provisioning services also remained enjoyable by the entities standing on the far at recipient end (Fig. 23.3) (Ajonia 2011). Thus, different PES schemes gave answers and established links between end-users and service regulator managers and an easy flow of compensations. This ensures a steady monetary flow from the end-users of the services to the ESs

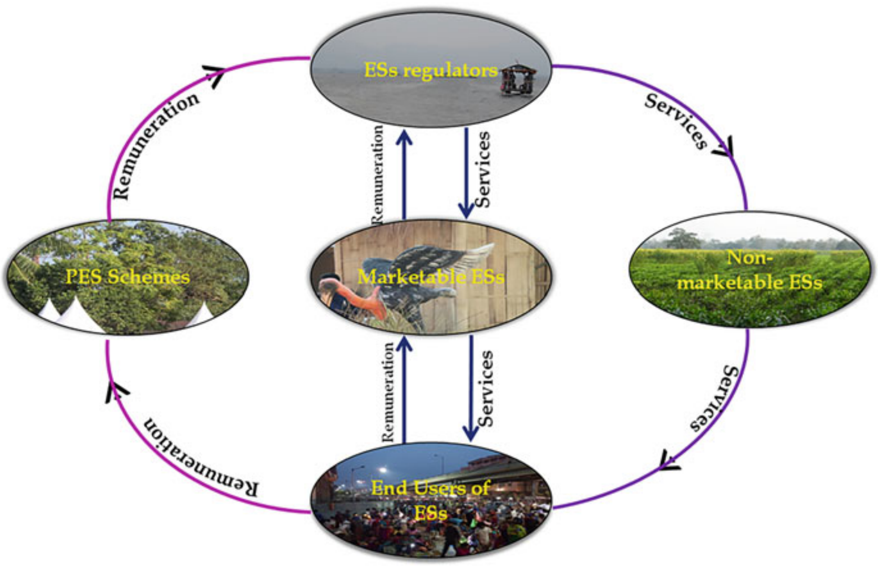

Fig. 23.3 Schematic flow chart of payment on ecosystem services. *ESs* environmental services (Ajonia 2011)

regulators. The following flow chart elaborates the schematic flow of the services and returns benefits:

The remuneration systems can be practised in several ways through which the ESs regulator may benefit directly or indirectly. For example, water purification and shed protection (example of upstream and downstream communities) ensured quality and quantity of water and control over erosion and floods through mixed planting. The end-users, i.e., the downstream community, ensure monetary supply through a structured institutional PES system to ensure the services are under a voluntary payment mechanism. This could establish a link between the upstream and downstream community and keep the unrestricted quality flow of the ESs (Bhatta and Pandit 2015). Another example is that carbon-oriented management practices through PES schemes have become a prominent option in global GHG reduction. Through both short term and long-term carbon credits, the ESs regulators can directly be benefited, thereby storing the CO_2 in their farms. This will increase participation of the regulators and the end-users to directly in the PES schemes and provide co-benefit to the global environment (Coderoni et al. 2014).

23.4 Case Studies and Examples of PES in Asia and Africa

Globally, 205 active PES programmes were identified just for watershed services, with a further 76 projects in development by 2013 (Suich et al. 2017). Through a review of the literature, Namirembe et al. (2014) identified 50 PES projects in Africa, consisting of 27 carbon sequestration and emission reduction, 17 biodiversity conservation, 2 watershed function and 4 bundled E.S. Many of those projects fall within the 'softer' PES paradigm with characteristics of co-investment (Namirembe et al. 2014). In the following sections, we will provide examples of successful examples.

23.4.1 PES Scheme in Bushenyi District, Uganda

Following the National Forest Plan of Uganda (2002), there was a need to raise investments in the forest sector to implement the projects on carbon sequestration (Distefano 2011), which had direct benefits on socio-economy, and national poverty eradication policy and sustainable development. Under these circumstances, a system of projects was developed by Plan Vivo Foundation. Ecotrust managed the PES project, a local conservation NGO in the Bushenyi District, where a patchwork of subsistence farms planted with bananas, maize, coffee, sugarcane, sweet potatoes, etc. The project's key objective was to enable communities of farmers to access the emerging voluntary carbon market by combining carbon sequestration with sustainable rural development. A group of carbon buyers supported the project; they were informed about the possibility of purchasing carbon offset certificates through resellers and brokers. As a result, around 500 farmers joined the project and participants were advised to plant according to three systems: boundary planting, agroforestry or woodlot planting. The Plan Vivo System ensures that an average of 60% of the carbon offset purchase income goes directly to communities through instalments disbursed over a decade.

The initiated project had developed the plantation of 400 trees ha^{-1} in that region's degraded and cultivable lands, mostly timber and other tree species of high local importance. It was assessed that annually such woodlots could potentially sequester nearly 226 Mg carbon dioxide over in 25–50 years. To overcome the further deforestation led by the plantation projects, Plan Vivo targeted farmers who could keep a minimum of one-hectare land for tree planting. Nearly 60% of the income generated through carbon offset purchase was commuted to the communities involved in the project and disbursed into instalments through local microfinance institutions (Distefano 2011). Farmers now manage 692 ha of land for an emission reduction capacity of 80,000 tonnes of carbon dioxide equivalent per annum. The project has been validated and verified by an independent third party: the Rainforest Alliance.

23.4.2 Tree Planting in the Lake Victoria Basin, Kenya

The introduction of water hyacinth in Lake Victoria brought a disastrous effect to the ESs provided by the lake and hindered fishing by local fishers. Lake degradation was further aggravated by the deforestation occurring around the Nyando and Yala watershed area to cultivate food crops (Kagombe et al. 2018). This resulted in lake sedimentation of 1–3 million tonnes $year^{-1}$. The Kenya Agricultural Research Institute (KARI) and ICRAF initiated a project called 'Western Kenya Integrated Ecosystem Project' in 2005 to restore the watershed areas by converting cropland to agroforestry systems with funds from the World Bank. The project aimed to restore the severely degraded areas with plantations, thereby reducing soil erosion, enhancing carbon stock, and reducing sedimentation load from the watershed region. In a survey for implementing the PES scheme, farmers were more interested in planting the received seedling and their cropland upon receiving direct incentives in the form of seedling subsidies (Jindal 2010; Jindal et al. 2008). The findings of this programme show that incentives in the form of a seedling subsidy can increase the likelihood of reforestation programmes. In the Nyando and Yala Basins, increased use of Eucalyptus trees, consequent to the government prohibition to log native forest species, has already been reported. Farmer preferences for exotic species are alarming considering the long term ecological disaster associated with the use of exotic species on drylands and the already degraded ecological conditions of the Lake Victoria basin (FAO 2011).

23.4.3 Emiti Nibwo Bulora Project in Tanzania

The PES scheme was initiated in 2008 in the Bugeneand Kaisho zones of Karagwe district in the Kagera province of Tanzania (FAO 2011). The scheme focused on rewarding farmers for carbon sequestration in soil and perennial plants through agroforestry and agronomic practices. This initiative was promoted by the Swedish Cooperative Centre (SCC) in collaboration with the Swedish Vi Agroforestry Programme (ViAFP). The Project also involved Plan Vivo, which independently assesses the reduction of carbon emissions and generates. Plan Vivo certificates are sold exclusively on the voluntary market. The project covered an area of 15.9 ha, with 23 small-scale farmers participating with individual landholdings of between 0.06 and 1 ha. The PES agreement for carbon sequestration requires improved soil management and agroforestry systems. Farmers design their management plan, including boundary planting, woodlots, fruit orchards and dispersed inter-planting. Grazing and tree-cutting during the contract period were not allowed. Payments to participants are in cash, distributed over five instalments during the 10-year contracts. Plan Vivo carried out the first carbon reduction certification in 2010, and the first payment was in June 2010, according to the Plan Vivo offset standard system. In total, 14 farmers have qualified for the first payment. Based on the adopted technologies, payments depend on the individual participants' land use plans and technical specifications for carbon sequestration. The buyer at the pilot stage was the Vi Agroforestry Programme. Yet, private companies (primarily in Sweden) are the target group in the future and potential internal upscaling of the project. The total emissions reduction capacity of the project was estimated at 40,000 tonnes of carbon dioxide per year (FAO 2011).

23.4.4 Rubber Agroforestry in Bungo District, Indonesia

Natural rubber is one of the major export commodities supporting over a million households in Indonesia. Of the total Indonesian geographical area, smallholder rubber solely constitutes 83% of it and accounts for 68% of the total latex production of the country (Wibawa et al. 2005). Older rubber agroforests harboured the most species accumulation than the plantations and forests and were the cultivated landscape bird species (Beukema et al. 2007). Economically, 69% of the total farmers' income is derived from rubber cultivation and other off-and-on farm activities like rice production, collection and sale of timber and non-timber forest products, etc. (Wibawa et al. 2005). Such agroforestry systems have induced an impact on climate change. Due to income opportunities, farmers disregard the slash and burn practice of agriculture, thus potentially restricting the GHG index globally. The annual income thus generated by different rubber agroforestry and smallholder rubber systems was primarily used in the households' nutritional requirements and other expenses like clothing and societal requirements (Fig. 23.4).

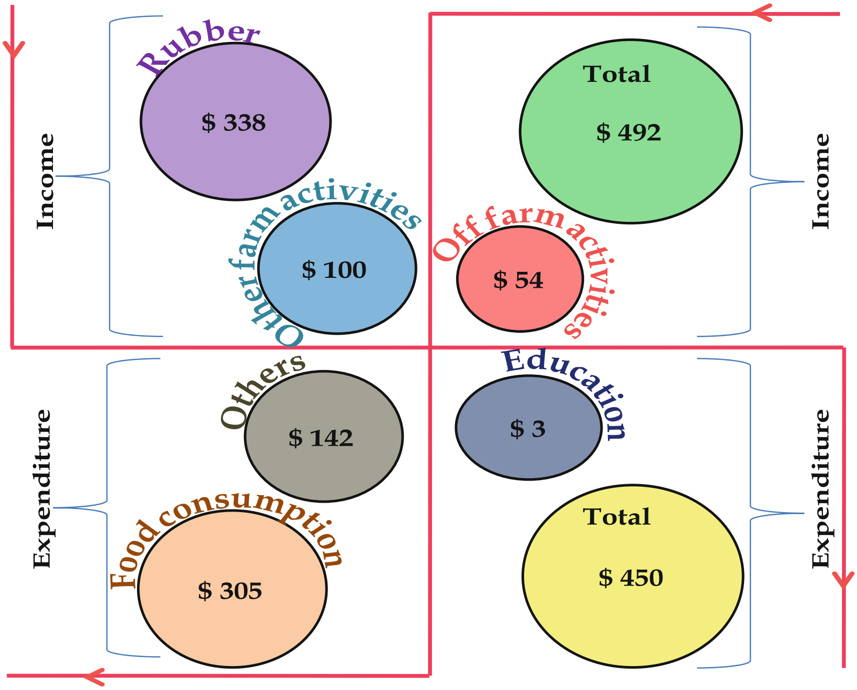

Fig. 23.4 Annual average in-and-outflow of cash generated through rubber agroforestry systems in Indonesia (Wibawa et al. 2005)

The World Agroforestry Centre (ICRAF) launched pilot projects to implement PES in the Bungo district of Indonesia in 2004 to conserve the rich biodiversity of rubber agroforestry system by reward mechanism to the farmers (Joshi et al. 2011). As per RUPES (Rewarding Upland Poor for Environmental Services) assessment, these agroforestry systems were rich with 971 tree species and 37 mammal species, including 9 endangered species listed by CITES (Joshi et al. 2011). The incentives rewarded include support in the establishment of a small hydropower plant, the establishment of nurseries, and clones of high yielding rubber trees. In addition, however, RUPES sought to consider schemes for eco-certification of managed complex rubber agroforests fetching premium price at local markets and possibly building carbon and water quality together with biodiversity (Leimona and Joshi 2010; Joshi et al. 2011).

23.4.5 Multi-Strata Coffee Gardens in Sumberjaya, Indonesia

Since the 1970s, deforestation has been occurring in the watershed region of the Besai river by smallholder coffee cultivars. Consequently, it took sediment discharge to the established hydropower plant because of the soil erosion from the deforested areas (USAID 2007). As a result, farmers were evicted from their agricultural settlements after declaring nearly 40% of the areas for restricted use. Later in 1998, to resolve these arose social conflict and promote the mutually profitable land use management, a negotiation took place between ICRAF and the local NGO (Joshi et al. 2011). When the evictions remained unsuccessful, a legal order program called 'Hutan Kamasyarakatan' was established similar to a PES scheme. The program gave permission to the community to utilize the land for the non-forest purpose and who are committed to protecting the native forest and converting monoculture coffee to multistrata coffee gardens. The 'Hutan Kamasyarakatan' success was also elevated by the RUPES programs initiated in 2004. Under joint initiative, nearly 6500 cultivators had received land tenure conditionally and average annual households' income had also increased by 30% (Joshi et al. 2011).

RUPES is engaged in the pilot survey and River Care between the river basin and the hydroelectric power plant using private funded PES schemes. Under the initiative RUPES has made payments to the cultivators who are actively engaged in the reduction of the sedimentation load on the river due to soil erosion (Fig. 23.5).

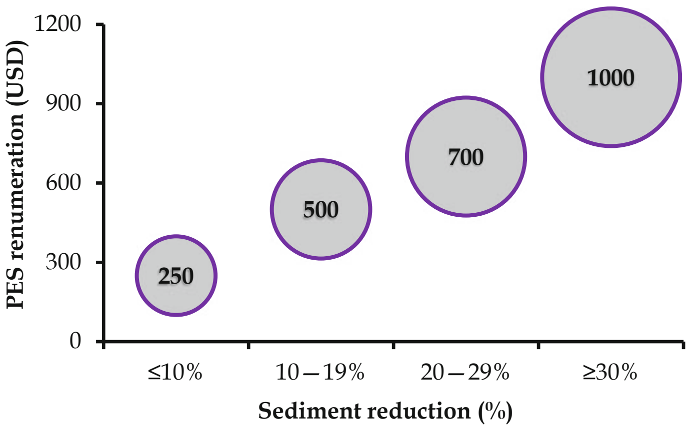

Fig. 23.5 Scheme of payment for reduction of river sedimentation

23.4.6 Coffee Agroforestry in India

The CAFNET programme, Connecting Environmental Services and Market Values of Coffee Agroforestry, implemented in major coffee agroforest regions in Central America, East Africa and India, aims to link sustainable management and the environmental benefits of coffee agroforests with appropriate remuneration for producers through providing a better access to markets and payment for environmental services. This involves finding ways to improve livelihoods for coffee farming communities while at the same time conserving natural resources. In the state of Karnataka, Kodago district is one of the famous coffee producers in the region, mainly growing under native tree species in the form of agroforestry systems. In Kodagu district, mandarin, citrus fruits, arecanut and banana can be found interspersed with coffee and vanilla, palm oil, and ginger cultivation to supplement income (Chengappa et al. 2017). However, rice was cultivated in the terrace of lowlands before the beginning of the coffee agroforestry system. Currently, it occupies nearly 33% of the total area of the district and is recognized for its implication in different ESs like conservation of biodiversity recreational and cultural significance of the landscapes. Moreover, the system provides invaluable E.S., such as recharging groundwater, enhanced carbon sequestration potentials, high biodiversity, etc. Since 2009, eco-labelling of the coffee produced were started in the region, and initially, products of six farmers were certified, hence securing high prices of their produce (Garcia et al. 2011). To help farmers add value to their coffee through better access to markets and eco-certification schemes with 7 farmer groups certified by Rain Forest Alliance and/or UTZ Certified. Together with product labelling, the district of Kodago also seeks landscape labelling through various PES schemes because of the high E.S. of the region and to sustain the well-structured and managed systems of high environmental importance (Garcia et al. 2011).

23.5 Challenges and Opportunities

PES is expected to work where ESs are under some degree of present or future threat and where the opportunity costs for alternative land use are not elevated (Wunder 2007). These situations are often found in human-modified agroecosystems (such as degraded pastures, marginal croplands, and hillside remaining forest patches), where the original natural capital has already been exploited, and the resulting degraded ecosystems have lost their resilience (FAO 2011). In such circumstances, agroforestry is said to be a win-win solution in terms of restoring ecosystem functions and the willingness of farmers to accept payment (Haile et al. 2019; Murniati et al. 2022; Porras 2010). For example, Porras (2010) found that the number of smallholder contracts has increased due to including agroforestry as a category in PES schemes in Costa Rica. Haile et al. (2019) found that farmers in Ethiopia strongly prefer food as the mode of payment than cash and short-term contracts to grow trees on their agricultural land.

Although many studies provide evidence for the eligibility of agroforestry under PES financing mechanisms, payment is ultimately attached to forest cover as a tradable ecosystem service (Haile et al. 2019). Numerous factors influence the participation of local people in the PES program. These include; gender, resource endowment, financial and in-kind incentives, and positive environmental perceptions (Waruingi et al. 2021). In analysis of a project called Plantation Establishment Livelihood Improvement Scheme (PELIS), Waruingi et al. (2021) found that participation of women and poor community members was limited, although the PELIS program seeks to promote the involvement of marginalized groups, there. The key reasons for low participation by women rest on the fact that they are constrained by reproductive (e.g. child care) and productive roles (e.g. provision of farm labour, food preparation, water and fuelwood collection, etc.) and high program costs. In addition, limited access to and control of resources such as land and other productive assets means that women may lack access to credit to invest in necessary inputs and engage in sustainable management practices. Other studies have shown that initial investment costs limit poorer households, lack of access to information and skills, technical capacity and resources needed to participate in government-sponsored forest incentive programs meaningfully (Clements and Milner-Gulland 2015; Zbinden and Lee 2005).

Studies provide evidence that incentives and benefits from PES can promote participation. However, it is also notable that incentive incompatibilities across different benefits can also dissuade participation. Factors directly associated with ecosystem conservation, such as perception of positive forest cover change and establishment of woodlots on own farms, also influenced households' intensity of participation in PES (Waruingi et al. 2021). Comparable outcomes were reported in the Mau Forest complex in Kenya, where ownership of private woodlots was positively associated with increased participation in environmental conservation (Okumu and Muchapondwa 2020). Further, the findings show that households who perceived that forest cover had increased over the past few years were more likely to participate at a higher intensity. The observation implies that while households' participation levels could be motivated by monetary and in-kind benefits, the desire to ensure a sustainable forest ecosystem can also influence a higher intensity of involvement in PES. Similar findings have been reported in Mexico and Bolivia (Bottazzi et al. 2018), suggesting that a genuine interest in resource conservation may drive households' participation in conservation initiatives.

23.6 Conclusions and Recommendations

We conclude that PES can be an excellent mechanism to incentivize farmers to preserve forest patches on their land through agroforestry interventions or converting degraded cropland into agroforestry systems. However, the application of PES in agroforestry has received little attention in U.N. Framework Convention on Climate Change programmes. Additionally, information about the on-the-ground application of PES from agroforestry is scanty. There are several social, economic, institutional, and policy barriers to the widespread adoption of PES from agroforestry. Poor institutional readiness and lack of mechanisms to reward farmers/land managers through PES are critical issues that need to be addressed. Translation of science into on-the-ground action necessitates close cooperation of researchers and extension staff with the private sector, policymakers, and land managers.

References

Ajonia G (2011) Assessing policy and institutional frameworks for Reward Based Approaches for Watershed and biodiversity management: current practices, constraints and prospects in Cameroon. World Agroforestry Centre, Nairobi, Kenya, pp 13–25

Akinnifesi FK, Ajayi OC, Kwesiga F, Sileshi GW, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) (2008a) Indigenous fruit trees in the tropics: domestication, utilization and commercialization. CAB International, Wallingford

Akinnifesi FK, Sileshi G, Ajayi OC, Chirwa PW, Kwesiga F, Harawa H (2008b) Contributions of agroforestry research and development to livelihood of smallholder farmers in Southern Africa: 2. Fruit, medicinal, fuelwood and fodder tree systems. Agric J 3:76–88

Akinnifesi FK, Ajayi OC, Sileshi G, Chirwa PW, Chianu J (2010) Fertiliser trees for sustainable food security in the maize-based production systems of east and southern Africa. A review. Agron Sustain Dev 30:615–629

Anderson SH, Udawatta RP, Seobi T, Garrett HE (2009) Soil water content and infiltration in agroforestry buffer strips. Agr Syst 75:5–16

Baral H, Keenan RJ, Stork NE, Kasel S (2014) Measuring and managing ecosystem goods and services in changing landscapes: a south-east Australian perspective. J Environ Plan Manag 57: 961–983

Bayala J, Sileshi WG, Coe R, Kalinganire A, Tchoundjeu Z, Sinclair F, Garrity D (2012) Cereal yield response to conservation agriculture practices in dry lands of West Africa: a quantitative synthesis. J Arid Environ 78:13–25

Beukema H, Danielsen F, Vincent G, Hardiwinoto S, van Andel J (2007) Plant and bird diversity in rubber agroforests in the lowlands of Sumatra, Indonesia. Agr Syst 70:217–242

Bhatta DB, Pandit A (2015) Payment for ecosystem services: possible policy instrument for ecosystem based adaptation in Nepal. In: National Workshop on Payment for Ecosystem Services: opportunities and challenges in Nepal, pp 17–19

Bhatta LD, van Oort BEH, Rucevska L, Baral H (2014) Payment for ecosystem services: possible instrument for managing ecosystem services in Nepal. Int J Biodivers Sci Ecosyst Serv Manag 10:289–299

Bottazzi P, Wiik E, Crespo D, Jones JPG (2018) Payment for environmental “self-service”: exploring the links between farmers’ motivation and additionality in a conservation incentive programme in the Bolivian Andes. Ecol Econ 150:11e23

Brahma B, Pathak K, Lal R, Kurmi B, Das M, Nath PC, Nath AJ, Das AK (2018) Ecosystem carbon sequestration through restoration of degraded lands in Northeast India. Land Degrad Dev 29: 15–25

Capodaglio AG, Callegari A (2018) Can payment for ecosystem services schemes be an alternative solution to achieve sustainable environmental development? A critical comparison of implementation between Europe and China. Resources 7:40. https://doi.org/10.3390/resources7030040

Cassman KG (1999) Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc Natl Acad Sci U S A 96:5952–5959
Chakeredza S, Hove L, Akinnifesi FA, Franzel S, Ajayi O, Sileshi G (2007) Managing fodder trees as a solution to human-livestock food conflicts and their contribution to income generation for smallholder farmers in southern Africa. Nat Res Forum 31:286–291
Chengappa PG, Devika CM, Rudragouda CS (2017) Climate variability and mitigation: perceptions and strategies adopted by traditional coffee growers in India. Clim Dev 9:593–604
Chirwa PW, Akinnifesi FK, Sileshi G, Syampungani S, Kalaba FK, Ajayi OC (2008) Opportunity for conserving and utilizing agro-biodiversity through agroforestry in southern Africa. Biodiversity 9:45–48
Clements T, Milner-Gulland EJ (2015) Impact of payments for environmental services and protected areas on local livelihoods and forest conservation in northern Cambodia. Conserv Biol 29(1):78–87
Coderoni S, Longhitano D, Vinci A (2014) Payment for ecosystem service for carbon credits from Italian olive groves. Some issues regarding the mode of payment. Int J Food Agri Econ 2:63–80
Daily GC (1997) Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC
Distefano E (2011) Plan vivo: a voluntary carbon sequestration PES scheme in Bushenyi district, Uganda. In: Payments for ecosystem services and food security. FAO, Rome, pp 227–233. http://www.fao.org/3/i2100e/i2100e.pdf
Ezzine-de-Blas D, Wunder S, Ruiz-Pérez M, Moreno-Sanchez RP (2016) Global patterns in the implementation of payments for environmental services. PLoS One 11(3):e0149847
FAO (2011) Payments for ecosystem services and food security. Food and Agricultural Organization of the United Nations, Rome
Fripp E (2014) Payments for Ecosystem Services (PES): a practical guide to assessing the feasibility of PES projects. Center for International Forestry Research, Bogor, Indonesia
Garbach K, Lubell M, DeClerck FAJ (2012) Payment for ecosystem services: the roles of positive incentives and information sharing in stimulating adoption of silvopastoral conservation practices. Agric Ecosyst Environ 156:27–36
Garcia C, Ghazoul J, Kushalappa C (2011) Geographical indications and landscape labelling in Kodagu district, India. In: Payments for ecosystem services and food security. FAO, Rome, pp 227–233. http://www.fao.org/3/i2100e/i2100e.pdf
Garrett HE, McGraw RL (2000) Alley cropping practices. In: Garrett HE, Rietveld WJ, Fisher RF (eds) North American agroforestry: an integrated science and practice. ASA, Madison, pp 149–188
Garrity DP (2004) Agroforestry and the achievement of the millennium development goals. Agr Syst 61:5–17
Geist JH (2000) Transforming the fringe: tobacco-related wood usage and its environmental impact. In: Majoral R, Jussila H, Delgado-Cravidao (eds) Environment and marginality in geographical space. Ashgate, Aldershot, pp 87–118
Global Environment Facility (2014) GEF investments on payment for ecosystem services schemes. World Bank, Washington, DC
Haile KK, Tirivayi N, Tesfaye W (2019) Farmers' willingness to accept payments for ecosystem services on agricultural land: the case of climate-smart agroforestry in Ethiopia. Ecosyst Serv 39:100964. https://doi.org/10.1016/j.ecoser.2019.100964
Harvey CA, Gonzales JG, Somarriba E (2006) Dung beetle and terrestrial mammal diversity in forest, indigenous agroforestry systems and plantain monocultures in Talamanca, Costa Rica. Biodivers Conserv 15:555–585
Heal G (2000) Nature and marketplace, capturing the value of ecosystem services. Island Press, Washington. https://islandpress.org/books/nature-and-marketplace
Hubermann D (2009) A gateway to PES: using payments for ecosystem services for livelihoods and landscapes. In: Markets and incentives for livelihoods and landscapes series no. 1, Forest

conservation programme. International Union for the Conservation of Nature (IUCN), Gland. https://www.iucn.org/sites/dev/files/import/downloads/a_gateway_to_pes_d_huberman.pdf
IPCC (2000) Emission scenarioas, special report, summary for policy makers, Working Group III. International Panel for Climate Change, Geneva
Jack BK, Jayachandran S (2018) Self-selection into payments for ecosystem services programs. Proc Natl Acad Sci U S A 116:5326–5333
Jack BK, Kousky C, Sims KRE (2008) Designing payments for ecosystem services: lessons from previous experience with incentive-based mechanisms. Proc Natl Acad Sci 105:9465–9470
Jamnadass R, Dawson I, Franzel S, Leakey RRB, Mithöfer D, Akinnifesi FK, Tchoundjeu Z (2011) Improving livelihoods and nutrition in sub-Saharan Africa through the promotion of indigenous and exotic fruit production in smallholders' agroforestry systems: a review. Int For Rev 13:338–354
Jayachandran S (2013) Liquidity constraints and deforestation: the limitations of payments for ecosystem services. Am Econ Rev 103(3):309–313
Jayachandran S, de Laat J, Lambin E, Stanton C (2017) Cash for carbon: a randomized trial of payments for ecosystem services to reduce deforestation. Science 357(6348):267–273
Jindal R (2010) Livelihood impacts of payments for forest carbon services: field evidence from Mozambique. In: Tacconi L, Mahanty S, Suich H (eds) Payments for environmental services. Forest conservation and climate change. Edward Elgar, Cheltenham, pp 185–211
Jindal R, Swallow B, Kerr J (2008) Forestry-based carbon sequestration projects in Africa: potential benefits and challenges. Nat Resour Forum 32:116–130
Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agr Syst 76:1–10
Joshi L, Pasha R, Mulyoutami E, Beukema HJ (2011) Rubber agroforestry and PES for preservation of biodiversity in Bungo district, Sumatra. In: Payments for ecosystem services and food security. FAO, Rome, pp 114–135
Kagombe JK, Cheboiwo JK, Gichu A, Handa C, Wamboi J (2018) Payment for environmental services: status and opportunities in Kenya. J Resou Dev Manag 40. https://www.iiste.org/Journals/index.php/JRDM/article/view/40771/41925
Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: implications for the management of a smallscale carbon sink project. For Ecol Manage 246:208–221
Kronenberg J, Hubacek K (2013) Could payments for ecosystem services create an "ecosystem service curse"? Ecol Soc 18:10
Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. Agron Sustain Dev 39:47. https://doi.org/10.1007/s13593-019-0589-8
Kwesiga F, Coe R (1994) Potential of short rotation sesbania fallows in eastern Zambia. For Ecol Manage 64:161–170
Lee KH, Jose S (2003) Soil respiration and microbial biomass in a pecan–cotton alley cropping system in southern USA. Agr Syst 58:45–54
Leimona B, Joshi L (2010) Eco-certified natural rubber from sustainable rubber agroforestry in Sumatra, Indonesia. Project Final Report. World Agroforestry Centre (ICRAF), Bogor
Luedeling E, Sileshi G, Beedy T, Dietz J (2011) Carbon sequestration potential by agroforestry in Africa. In: Kumar BM, Nair PKR (eds) Carbon sequestration in agroforestry systems. Springer, Dordrecht, pp 61–83
Mafongoya PL, Sileshi GW (2020) Indices to identify and quantify ecosystem services in sustainable food systems. In: Rusinamodzi L (ed) The role of ecosystem services in sustainable food systems. Elsevier, Amsterdam, pp 43–71. https://doi.org/10.1016/B978-0-12-816436-5.00003-2
McNeely JA (2004) Nature vs nurture: managing relationships between forests, agroforestry and wild biodiversity. Agr Syst 61:155–165
MEA (2005) Millennium ecosystem assessment. Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Mishra PK (2011) Soil fertility management in agroforestry system. Int J Biotechnol Biochem 7: 637–644

Muchane MN, Sileshi GW, Gripenberg S, Jonsson M, Pumarino L, Barrios E (2020) Agroforestry boosts soil health in the humid and sub-humid tropics: a meta-analysis. Agric Ecosyst Environ 295:106899. https://doi.org/10.1016/j.agee.2020.106899

Murniati, Suharti S, Minarningsih, Nuroniah HS, Rahayu S, Dewi S (2022) What makes agroforestry a potential restoration measure in a degraded conservation forest? Forests 13:267. https://doi.org/10.3390/f13020267

Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23

Namirembe S, Leimona B, van Noordwijk M, Bernard F, Bacwayo KE (2014) Co-investment paradigms as alternatives to payments for tree-based ecosystem services in Africa. Curr Opin Environ Sustain 6:89–97

Nath AJ, Sileshi GW, Laskar SY, Pathak K, Reang D, Nath A, Das AK (2021) Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's nationally determined contribution. J Clean Prod 281:124831. https://doi.org/10.1016/j.jclepro.2020.124831

National Forest Plan of Uganda (2002) The national forest plan. Ministry of Water, Land and Environment, The Republic of Uganda, p 178

Okumu B, Muchapondwa E (2020) Welfare and forest cover impacts of incentive based conservation: evidence from Kenyan community forest associations. World Dev 129:104890

Pagiola S, Platais G (2002) Forthcoming, payments for environmental services: from theory to practice. World Bank, Washington, DC

Pagiola S, Rios AR, Arcenas A (2008) Can the poor participate in payments for environmental services? Lessons from the Silvopastoral project in Nicaragua. Environ Dev Econ 13:299–325

Paterson R, Karanja G, Nyaata O, Kariuki L, Roothaert R (1998) A review of tree fodder production and utilization within smallholder agroforestry systems in Kenya. Agr Syst 41:181–199

Pirard R (2012) Market-based instruments for biodiversity and ecosystem services: a lexicon. Environ Sci Policy 19–20:59–68

Porras I (2010) Fair and green? Social impacts of payments for environmental services in Costa Rica. International Institute for Environment and Development (IIED), London

Pumariño L, Sileshi GW, Gripenberg S, Kaartinen R, Barrios E, Muchane MN, Midega C, Jonsson M (2015) Effects of agroforestry on pest, disease and weed control: a meta-analysis. Basic Appl Ecol 16:573–582. https://doi.org/10.1016/j.baae.2015.08.006

Reang D, Sahoo UK, Giri K, Hazarika A, Nath AJ (2021) Ethnic homestead forests of North East India revealed as diverse land-use systems. Agrofor Syst 96:465–478

Salzman J, Bennett G, Carrol N, Goldestein A, Jenkins M (2018) The global status and trends of payments for ecosystem services. Nat Sustain 1:136–144

Schroth G, Sinclair F (2003) Trees crops and soil fertility: concepts and research methods. CABI, Wallingford, p 464

Schroth G, da Fonseca GAB, Harvey CA, Gascon C, Vasconcelos H, Izac AN (2004) Agroforestry and biodiversity conservation in tropical landscapes. In: Atangana A, Khasa D, Chang S, Degrande A (eds) Tropical agroforestry. Springer, Dordrecht, pp 227–232

Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agr Syst 60:123–130

Shreshta BM, Chang SX, Bork EW, Carlyle CN (2018) Enrichment planting and soil amendments enhance carbon sequestration and reduce greenhouse gas emissions in agroforestry systems: a review. Forests 9:369

Sileshi G, Mafongoya PL, Kwesiga F, Nkunika P (2005) Termite damage to maize grown in agroforestry systems, traditional fallows and monoculture on nitrogen-limited soils in eastern Zambia. Agric For Entomol 7:61–69

Sileshi G, Kuntashula E, Mafongoya PL (2006) Effect of improved fallows on weed infestation in maize in eastern Zambia. Zambia J Agri Sci 8:6–12

Sileshi G, Akinnifesi FK, Ajayi OC, Chakeredza S, Kaonga M, Matakala P (2007) Contribution of agroforestry to ecosystem services in the Miombo eco-region of eastern and southern African. Afr J Environ Sci Technol 1:068–080

Sileshi G, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to planted fallow and green manure legumes in sub-Saharan Africa. Plant and Soil 307:1–19. https://doi.org/10.1007/s11104-008-9547-y

Sileshi G, Akinnifesi FK, Debusho LK, Beedy T, Ajayi OC, Mongomba S (2010) Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crop Res 116:1–13. https://doi.org/10.1016/j.fcr.2009.11.014

Sileshi GW, Mafongoya PL, Akinnifesi FK, Phiri E, Chirwa P, Beedy T, Makumba W, Nyamadzawo G, Njoloma J, Wuta M, Nyamugafata P, Jiri O (2014) Fertilizer trees. In: Encyclopedia of agriculture and food systems, vol Vol. 1. Elsevier, San Diego, pp 222–234

Strassburg B, Turner RK, Fisher B, Schaeffer R, Lovett A (2009) Reducing emissions from deforestation—the "combined incentives" mechanism and empirical simulations. Glob Environ Chang 19:265–278

Suich H, Lugina M, Muttaqin M, Alviya I, Sari G (2017) Payments for ecosystem services in Indonesia. Oryx 51:489–497

Tyndall J, Colletti J (2007) Mitigating swine odor with strategically designed shelterbelt systems: a review. Agr Syst 69:45–65

Udawatta RP, Gantzer CJ, Anderson SH, Garrett HE (2008) Agroforestry and grass buffer effects on pore characteristics measured by high-resolution X-ray computed tomography. Soil Sci Soc Am J 72:295–304

USAID (2007) USAID PES source book: lessons and best practices for pro-poor payments for ecosystem services. http://moderncms.ecosystemmarketplace.com/ repository/moderncms_documents/PES_ Sourcebook.1.Pdf

Waruingi E, Mbeche R, Ateka J (2021) Determinants of forest dependent household's participation in payment for ecosystem services: evidence from plantation establishment livelihood improvement scheme (PELIS) in Kenya. Glob Ecol Conserv 26:e01514

Wibawa G, Hendratno S, van Noordwijk M (2005) Permanent smallholder rubber agroforestry systems in Sumatra, Indonesia. In: Slash and burn: the search for alternatives. Columbia University Press, New York, pp 222–232

Williams-Guillen K, Perfecto I, Vandermeer J (2008) Bats limit insects in a tropical agroforestry system. Science 320:70

Wunder S (2007) The efficiency of payments for environmental services in tropical conservation. Conserv Biol 21:48–58

Wunder S (2015) Revisiting the concept of payments for environmental services. Ecol Econ 117: 234–243

Zbinden S, Lee DR (2005) Paying for environmental services: an analysis of participation in Costa Rica's PSA program. World Dev 33:255–272

Chapter 24
Agroforestry for Sustaining Industrial Raw Materials: Experience from a Value Chain Leveraged Consortium Model

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Abstract Agroforestry has received increasing attention by the agroindustry and forestry industry, private farmers and policy makers due to the increasing demand for wood and wood products coupled with declining supply from natural forests. This necessitated promotion of technology-based agroforestry to create self-reliance in raw material security besides catering to the needs of climate change mitigation and adaptation. Considering these developments into account, the Tamil Nadu Agricultural University in India conceived a value chain based on industrial agroforestry model and successfully implemented with increased participation of all stakeholders. This model has identified wide range of challenges and constraints along with research gaps that existed in the entire production to consumption system and resolved them through technological, organizational and marketing interventions. The establishment of a consortium of industrial agroforestry has created an institutional mechanism to address all the challenges and helped in establishing over 80,000 ha of value chain-based agroforestry plantations. To strengthen these developments, an exclusive agroforestry business incubator was established, and it is creating business enterprises in the form of start-ups and MSMEs, thereby leveraging technology-based agroforestry business enterprise development. The value chain model has made significant impact in terms of productivity (wood production: 25 m^3 ha^{-1} $year^{-1}$), profitability (B:C ratio of over 3:1), income and employment generation activities (over 300 men days per ha) and increased carbon sequestration (four million tonnes CO_2 equivalent). This value chain model is very unique and successful, which extends a greater scope of replication not only within the country but across the world as well.

Keywords Industrial agroforestry · Value chain-business incubator · Consortium model · Employment generation · Business enterprise

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24.1 Introduction

India is one of the largest producers and consumers of wood and wood products. The forests in the country have played a significant role in providing wood and wood products and act as a potential land use system to meet domestic and industrial wood products. However, the growing population, urbanization and industrialization have increased the wood demand of the country (Parthiban et al. 2014). The key industries like timber, plywood and panels, pulp and paper, packing case, match splints and sports goods consume huge volume of wood. The promulgation of Forest Conservation Act (Government of India 1980) followed by ban on felling trees imposed by the supreme court of India has reduced the supply of wood from natural forests (Parthiban et al. 2021a).

The growing demand coupled with restricted supply from natural forests has ushered in a mismatch between demand and supply. The actual wood demand for India has been estimated at 152 million m^3 of wood to meet the raw material requirement of organized wood-based industries (FAO 2009). In India, wide range of unorganized industries using wood and wood products is also increasing at an alarming rate. Similarly, the demand for wood energy both for domestic and industrial requirement is estimated at more than 380 million m^3 (Parthiban et al. 2021a, b). While the demand is increasing, there is no commensurate increase in the plantation sector to create self- reliance in raw material security. Part of this massive wood requirement can be met through imports and promotion of organized plantation programme in the form of agroforestry and farm forestry.

Considering these demand and development needs into account, the Government of India instituted a National Forest Policy (Government of India 1988) which directed all wood-based industries in the country to generate their own raw material by establishing suitable linkage with the farmers. However, for want of suitable institutional mechanism, the plantation promotion and development has been modest barring a few exceptions. Taking this deficiency into account, the Ministry of Agriculture and farmers' welfare in the year 2014 (Government of India 2014) enunciated a National Agroforestry Policy supportive of increased participation of wood-based industries in agroforestry promotion and development. Nevertheless, these developments and policy directions have not witnessed organized agroforestry development in the country due to the presence of wide range of challenges and constraints.

Against this backdrop, the Forest College and Research Institute of Tamil Nadu Agricultural University conceived a value chain model in the year 2004 and demonstrated in association with two paper industries in the State of Tamil Nadu. The successful model was amplified through ICAR-NAIP project on value chain on industrial agroforestry (Parthiban et al. 2014). This was further strengthened by establishment of a consortium of industrial agroforestry (Parthiban et al. 2019) and an agroforestry business incubator (Parthiban et al. 2020), which the created institutional mechanism to promote organized agroforestry to assure sustainability in industrial raw material generation. This chapter documents the major challenges faced, and outlines the technological and organizational interventions of the consortium model.

24.2 Identification of Challenges and Research Needs

Before conceiving a value chain system in agroforestry, the current research group carried out an intensive baseline survey and identified the challenges, constraints and the research gaps that existed in the entire production to consumption system in agroforestry (Parthiban and Rao 2008). These challenges and constraints were identified through a wide range of consultations, discussions, field visits and other stakeholder discussions. The identified constraints, challenges and research gaps are summarized in Fig. 24.1.

The constraints, challenges and the research gaps identified (Fig. 24.1) were resolved through organized and long-term participatory research and development mechanism in association with timber, plywood, match, energy, pulp and paper and other non-timber forest products (NTFP) industries. This has created an institutional

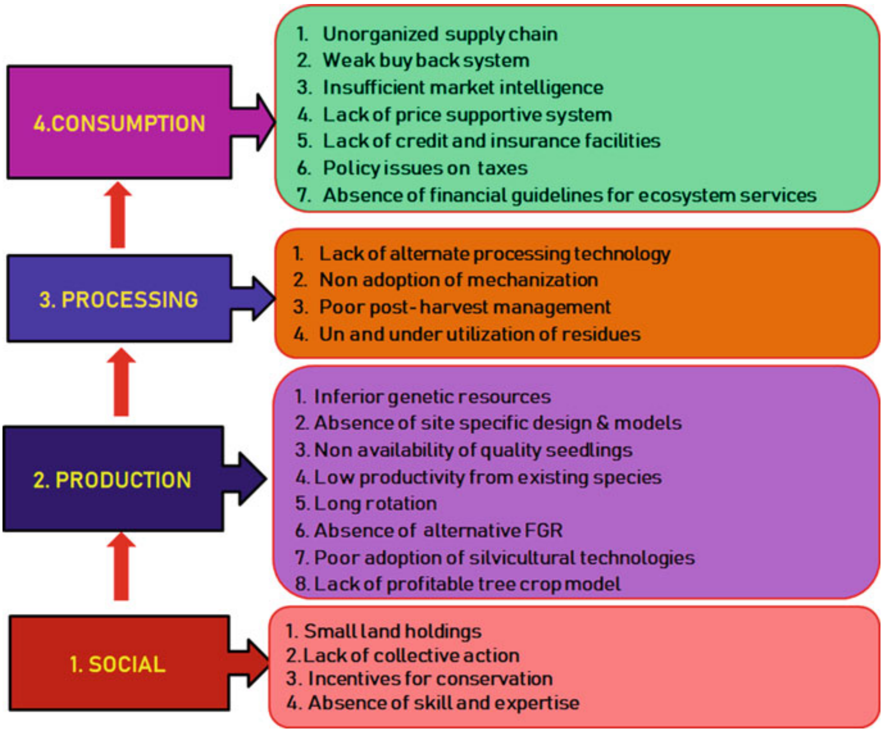


Fig. 24.1 Challenges and constraints that existed in agroforestry production to consumption system value chain innovations and interventions

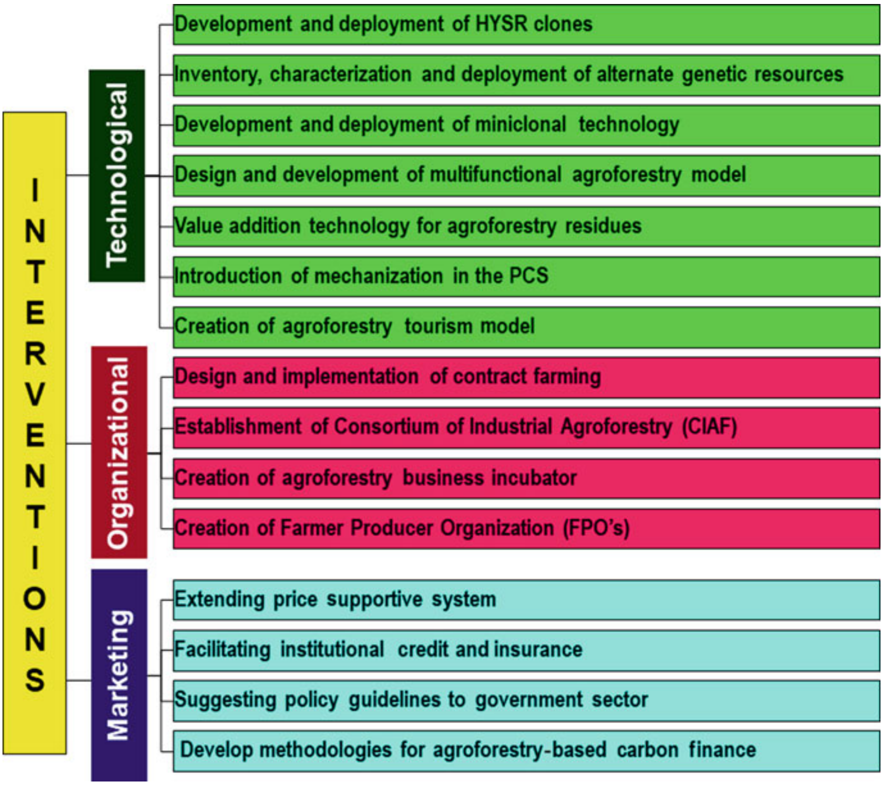


Fig. 24.2 Value chain innovations and interventions

mechanism to link all stakeholders in the form of Consortium of Industrial for Agroforestry. In a holistic perspective, a value chain model on industrial agroforestry was conceived and the challenges that exist were resolved through technological, organizational and marketing interventions as depicted in Fig. 24.2.

24.3 Technological Interventions

24.3.1 Development and Deployment of High Yielding Short Rotation (HYSR) Clones

During the journey of over a decade, 30 different tree species were prioritized and incorporated in systematic improvement programme through identification and evaluation of provenances, seed sources, progenies, clones and hybrid clones. Through this evaluation, a wide range of potential HYSR clones were screened and deployed in an industrial agroforestry promotional programme. The major value

Table 24.1 High yielding short rotation clones developed and deployed

Sl. no	Species	Improved varieties	Duration (years)	Wood biomass (Mg ha^{-1})
Pulpwood				
1	*Casuarina equisetifolia*	MTP-1	3–5	150–3 years; 250–5 years
		MTP-2		
		CJ-01		
2	*Eucalyptus camaldulensis*	MTP-1	5	130
3		EH LBT 01	5	150
4	*Melia dubia*	MTP-2	2	150
Plywood				
5	*Eucalyptus urograndis*	EG-01	5	150
6	*Melia dubia*[a]	MTP-1	5	175–200
		MTP-2	8	100
		MTP-3		
7	*Anthocephalus kadamba*	MTP-1	6	100
8	*Toona ciliata*	TC-02	6	150
Timber				
9	*Dalbergia sissoo*	DS-18	6–8	150
10	Gumhar (*Gmelina arborea*)	FCRI GA-08/09	6	500 kg per tree
High value trees				
11	Teak (*Tectona grandis*)	MTP TK-07	15	0.425 cubic m per tree
12	Red Sanders (*Pterocarpus santalinus*)	TNRS-01	16–18	100 kg heartwood per tree

[a]Number of trees per ha vary depending on the utility (pulp/core veneer/face veneer/timber)

chain system introduced in this model involved replacing seed-based unproductive genetic resources with clone-based agroforestry which has ensured higher productivity (over 25 m^3 ha^{-1} $annum^{-1}$), short duration (2–5 years) and uniform output. The potential clones developed and deployed in industrial agroforestry are summarized in Table 24.1.

24.3.2 New and Potential Alternate Genetic Resources

Most industries primarily depend on only a few species such as Eucalyptus (*Eucalyptus camaldulensis, E. tereticornis, E. urophylla, E. grandis,* etc.), poplars (*Populus deltoides*), teak (*Tectona grandis*), Sal (*Shorea robusta*) and pines (*Pinus roxburghii, P. wallichiana, P. excelsa, P. gerardiana*) depending on the products manufactured and the associated utilization. However, dependency on one or two species is a major threat not only to the industries but also to the tree growing farmers. Species like Eucalyptus have witnessed wide controversies which detracts

Table 24.2 Alternate genetic resources developed for various industrial utility

Species	Improved varieties	Biomass (Mg ha^{-1})	Duration (years)	Industrial utility
Acrocarpus fraxinifolius	FCRI-AF 07	150	6	Plywood/ Package
Australian Acacia's	AMH-9	200	3 pulp 6 ply	Pulpwood/ Plywood
Swietenia macrophylla	SM-18 SM-21	150	6	Plywood/ Timber
Khaya senegalensis	KS-01	100	10	Timber
Morus alba	V1	100	6	Plywood/ Pulpwood
Chukrasia tabularis	FCRICT-03	150	6	Plywood/ Timber
Sterculia alata	MTP-SA-03	100–125	8	Matchwood
Populus deltoides	G-48	80–100	6	Plywood/ Matchwood
Eucalyptus camaldulensis	EC-1,9,14,16	175–200	3 pulp 6 ply	Pulpwood/ Plywood
Silk cotton (*Ceiba pentandra*)	–	1000 pods $tree^{-1}$	6–40	Floss
Jatropha hybrids *(J. curcas* × *J. integerrima)*	CJH 12, CJH 9, CJH 13	3 kg $tree^{-1}$	2–30	Biofuel
Neem (*Azadirachta indica*)	MTPAI-01	20 kg $tree^{-1}$	5–40	Biofuel
Pongamia pinnata	MTP PP-01	40–50 kg $tree^{-1}$	7–50	Biofuel
Punnai (*Calophyllum inophyllum*)	MTPCI-07	40–50 kg $tree^{-1}$	5–40	Biofuel
Madhuca latifolia	TNML-21	40–50 kg $tree^{-1}$	8–50	Biofuel

the attraction of agroforestry promotion. To resolve these issues, the programme has been mandated to identify and develop new and alternative genetic resources. Accordingly, a wide range of new and alternative species have been introduced in the evaluation programme and within these species, desirable clones and improved genetic resources were identified and deployed in the industrial agroforestry programme. The alternative species and the improved genetic resources in each species along with the productivity are summarized in Table 24.2. MTP-SA-03 an improved variety of *Sterculia alata* is shown in Fig. 24.3.

Fig. 24.3 MTP-SA-03 an improved variety of *Sterculia alata*

24.3.3 Innovative Technology for Quality Seedling Production

Availability of quality planting material in a required volume at the time of requirement was the major challenges experienced by all levels of stakeholders. To resolve this issue, an innovative mini clonal technology was developed for a wide range of species like timber, plywood, pulp and paper, match wood, tree-borne oil seeds (TBOs) and NTFP resources. This mini clonal technology included establishment and management of mother garden and the associated controlled mass multiplication. For most of the species prioritized for industrial agroforestry promotion, clonal mother gardens were established to cater to the needs of quality seedling production. This technology ensured multiplication throughout the year and required minimal space and time. It also ensured massive reduction in production cost. This has been developed for wide range of species and commercialized through consortium nurseries (Parthiban et al. 2021a, b).

24.3.4 Design and Development of Industrial Agroforestry Model

The increasing demand for wood and wood products coupled with decreasing supply from natural forest has necessitated intensive promotion of agroforestry. Keeping this into account a pulpwood value chain-based agroforestry was conceptualized and implemented in 2005 in association with pulp and paper industries (Parthiban et al.

Table 24.3 Various industrial agroforestry model developed and deployed

Type of model	Year	Major genera/species	Major industry
Pulpwood	2005	Species of *Casuarina*, *Eucalyptus* and other alternate pulpwood species like *Melia*	Tamilnadu Newsprints and Papers Limited, Karur Seshasayee Paper Boards, Erode
Tree-born oil seeds	2007	*Jatropha curcas, Pongamia pinnata, Madhuca longifolia, Calophyllum inophyllum*	Bannari Amman Industries and Mission Biofuels
Match wood	2009	*Albizia falcataria, Ailanthus excelsa*	Vasan Match Works, Gudiyatham
Energy	2011	Species of *Leusaena, Casuarina, Eucalyptus*	Auromira Energy Industry, Chennai
Plywood	2013	Species of *Melia, Toona, Acrocarpus, Eucalyptus, Swietenia, Anthocephalus*	Ambiply panels and doors, Mettupalayam
Composite wood	2016	Species of *Melia, Eucalyptus, Toona, Swietenia, Artocarpus*	Century ply (P)Ltd., Chennai
Timber	2020	Species of *Tectona, Swietenia, Dalbergia, Leucaena*	Suresh Timbers, Madurai
Oil-based	2021	Neem (*Azadirachta indica*)	Coromandel Group of Companies, Chennai

2010). The success of this model has been expanded to plywood, match wood, energy, timber and oil seeds, which received greater attraction among the farmers and the associated wood-based industries (Durairasu and Parthiban 2013; Parthiban et al. 2011). The various industrial agroforestry models developed and deployed are summarized in Table 24.3. Some agroforestry models for plywood, pulpwood and timber are represented in Figs. 24.4, 24.5 and 24.6.

24.3.5 *Design and Deployment of Multifunctional Agroforestry Model*

During the journey of this programme, it was witnessed that most farms are small and marginal and incorporating trees in the land use system was a major challenge. Moreover, small farmers depend on agriculture for their livelihood and hence there was a need to design small holder agroforestry models to transition them into an economic and commercial agroforestry. For this purpose, an innovative multifunctional agroforestry model was designed and demonstrated. The models involved judicially incorporation of high value trees, timber, plywood, fruit, medicinal plants, moringa tree in 6 circles. The entire area was divided into 4 quadrats and planted with fodder, flower, food and curry leaf components representing one crop in each quadrat. The entire boundary is planted with TBOs. This model is integrated with one milk animal and two goats. This model has created significant attraction

Fig. 24.4 Agroforestry with *Casuarina* (**a**) and *Melia* (**b**) as pulpwood species in industrial agroforestry

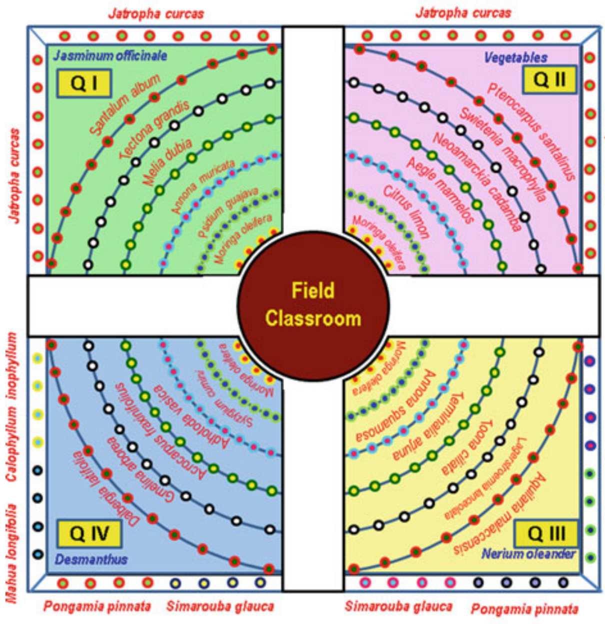
among the farmers and amplified across different agroecosystems and attracted more farmers towards agroforestry. This innovative model ensures a regular income (Parthiban et al. 2021a, b). The design of multifunctional agroforestry model along with the tree components demonstrated is presented in Fig. 24.7.

Fig. 24.5 Agroforestry with Eucalyptus (**a**) and *Anthocephalus kadamba* (**b**) for plywood and composite wood

24.3.6 Value Addition Technology

The promotion of agroforestry in general and industrial agroforestry in particular has witnessed the availability of significant volumes of residues in the form of twigs, small branches, barks, leafs, roots, etc. These residues accounted for about 10% to 20% of the total biomass generated from 1 hectare of plantations. Such a huge volume of residues was either unutilized or underutilized for want of suitable value

Fig. 24.6 Agroforestry with teak for timber



Tree species	Number of trees
Quadrat I	
Moringa oleifera	4
Psidium guajava	10
Annona mucronata	11
Melia dubia	11
Tectona grandis	12
Santalum album	12
Intercrops (Flowers)	
Jasminium officinale	72
Jasminium grandiflorum	104
Quadrat II	
Moringa oleifera	4
Citrus lemon	6
Aegle marmelos	11
Neolamarckia cadamba	11
Sweitenia macrophylla	11
Pterocarpus santalinus	12
Intercrops (Vegetables)	
Quadrat III	
Moringa oleifera	4
Annona squamosa	10
Terminalia arjuna	10
Toona ciliata	11
Lagestromia lanceolata	12
Aquilaria malaccensis	12
Intercrops	
Nerium oleander	28
Murraya koenigii	350
Quadrat IV	
Moringa oleifera	4
Syzygium cuminii	11
Adhotoda vasica	12
Acrocarpus fraxinifolius	12
Gmelina arborea	12
Dalbergia latifolia	12
Intercrops	
CO 3 Guinea grass	303
Desmanthus	
Border	
Jatropha curcas	50
Calophyllum inophyllum	5
Simaouba glauca	10
Pongamia pinnata	10
Madhuca longifolia	5
Total plants	1174

Fig. 24.7 The multifunctional agroforestry model

addition process and with institutional mechanism. Hence, a systematic value addition process was developed which translated agroforestry residues into a value-added briquettes and pellets. This enhanced employment and income generating activities through the creation of decentralized briquetting plant. Currently over ten such value addition centres have been created which enhanced the income generation to the tune of INR 7500 (~100US$) per metric ton of briquettes compared to INR 2000 of raw biomass. This value addition process has also augmented the development of self-reliance in raw material security for biomass-based energy generation thereby creating clean and green energy generation.

24.3.7 Introduction of Mechanization in Agroforestry Development

Agroforestry promotion and implementation has witnessed wide range of challenges and among them availability of skilled manpower to handle the activities from the entire production to consumption system is the most significant. The existing manpower is not skilled, and availability is a major threat. To resolve these issues, wide range of mechanization systems like mechanized pitting, in-situ harvesting, decentralized debarking and chipping have been created, which helped to address the issues of labour shortages.

24.4 Organizational Interventions

The lack of linkages among various stakeholders is considered as one of the major challenges and constraints. Due to this challenge, the entire production to consumption system has suffered for want of suitable institutional mechanism. Hence, organizational interventions were conceived and implemented to create strong linkages among stakeholders at all levels. These are briefly described below.

24.4.1 Design and Implementation of Contract Tree Farming

One of the first institutional arrangements developed to create organizational linkage is the design and implementation of contract tree farming. This contract tree farming extended technological support, assured buyback, price support system coupled with efficient linkages between the producers and consuming industries. Originally the contract farming model was designed for the paper industries and pronounced as contract pulpwood farming, which was implemented in association with two paper industries in Tamil Nadu. This attracted has significant interest among the farmers and extended greater scope of implementation to other industries (Parthiban et al. 2014; Parthiban and Rao 2008). Accordingly, a utility specific contract tree farming model was designed and implemented in association with Biofuel industry in 2007, matchwood industry in 2009, energy industry in 2011, plywood industry in 2013, timber industry in 2020 and oil industry in 2021 (Parthiban et al. 2020; Parthiban et al. 2021a, b).

24.4.2 Consortium of Industrial Agroforestry

One of the major organizational interventions was the creation of an exclusive Consortium of Industrial Agroforestry (CIAF) implemented from the year 2015 onwards. This consortium helped to create linkages among the stakeholders and increased the participation of a wide range of wood-based industries for effective collaboration and cooperation to accelerate agroforestry promotion and development. In addition, the consortium also extended a range of services. This included supply of quality planting materials through consortium nurseries, facilitating technological support for plantation establishment and felling operations through its felling institutions. Above all, participation of small and medium scale industries helped to resolve the issues in value-addition and increased participation helped to resolve marketing challenges (Parthiban et al. 2019, 2020). The consortium has proved to be a sustainable institutional mechanism, which now has 345 members (Fig. 24.8) incorporating all stakeholders involved in the entire production to consumption system.

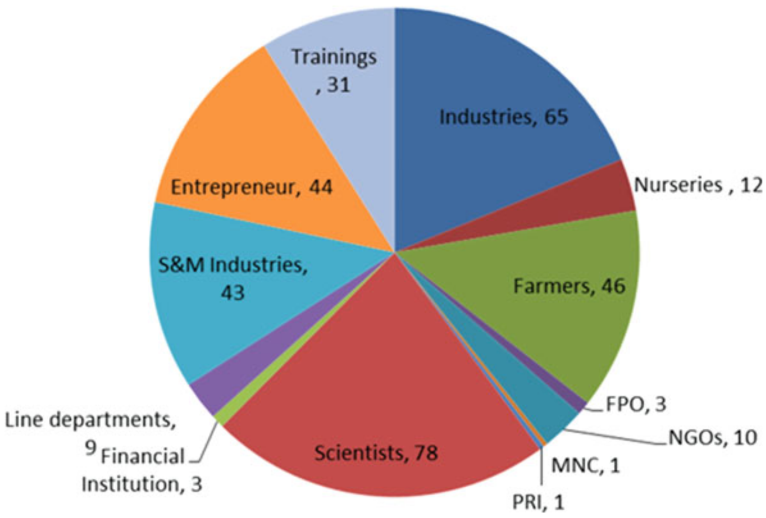


Fig. 24.8 Members of Consortium of Industrial Agroforestry

24.4.3 Agroforestry Business Incubator

The program established an exclusive Agroforestry Business Incubator, which is the first of its kind in the entire country. The basic objective of incubator is to create entrepreneurs by leveraging agroforestry technologies. The incubator has identified more than ten technologies and is involved in creating new entrepreneurs. It has successfully established 91 incubators (Fig. 24.9), who are supported with technology, managerial skills and market access. This has helped to create start-ups and MSMEs and extend a greater scope of income and employment generation activities by leveraging innovative technologies. The establishment of incubator is considered as one of the potential and sustainable organizational interventions which intensified agroforestry promotional activities.

24.4.4 Agroforestry Farmer Producer Organizations (FPOs)

Another major organizational intervention is the establishment of Agroforestry Farmer Producer Organizations (FPO). The value chain model has identified a wide range of business opportunities from the entire production to consumption system thereby extended a greater scope of creating organized institutions. Hence, the industrial agroforestry model established fie FPOs in the state of Tamil Nadu

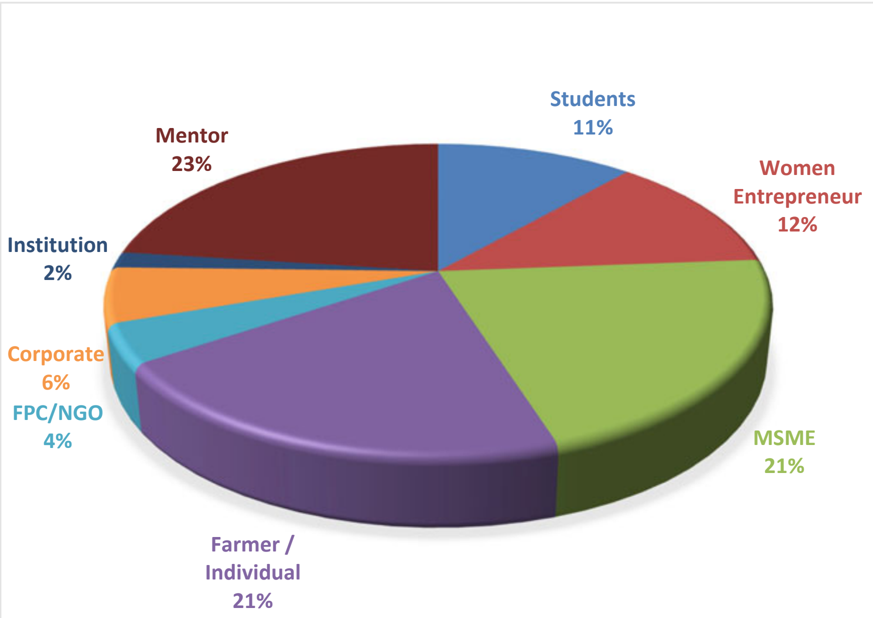


Fig. 24.9 Stakeholders of Agroforestry Business Incubator

representing one each in five agroclimatic zones. The FPOs were designed to establish business opportunities from production to marketing, thereby help to resolve the challenges. FPOs were also conceptualized to create income and employment generating activities to all tree growing farmers. This is at an early stage, which is expected to be one of the potential organizational interventions that help to accelerate agroforestry promotion.

24.5 Marketing Interventions

One of the major challenges and constraints faced by the stakeholders of industrial agroforestry in the area was the existence of multipartite supply chains and absence of a price supportive system. Due to these issues, agroforestry was considered as one of the unsuccessful land use systems. To mitigate these issues, consumption level intervention was established and implemented in association with wide range of stakeholders. The following are the major marketing interventions introduced and implemented.

24.5.1 Extending Price Supportive System

The value chain approach prioritized creating a price supportive system for a number of tree species amenable for agroforestry. Accordingly, elaborate consultations and discussions were conducted periodically and established price support systems for the tree species (Table 24.4).

24.5.2 Assured Buyback and Market Support

Another major intervention introduced in the value chain is assured buyback and market support for agroforestry products. Introduction of contract tree farming and the associated increased participation of wood-based industries in the value chain model have created an excellent platform for assured buyback and market for commodities. Unorganized supply chains have now been replaced with organized value-chain models, which assured buyback and marketing. This helped to extend more area under organized agroforestry.

Table 24.4 Price support system for various tree species

Species and clone	Girth (m)	Rate (INR Mg^{-1})
A. Plywood utility		
Melia dubia (MTP-1, MTP-2 and MTP-3)	0.45 and above	8500
	0.30–0.43	5000
	<0.30	3000
Eucalyptus camaldulensis (EH-LBT-01)	0.45 and above	6000
	0.30–0.43	3500
	<0.30	3000
Toona ciliata (MTPTC-02)	>0.45 and above	8500
Swietenia macrophylla (MTPSM-20)	0.45 and above	7000
Neolamarckia cadamba (MTP-1)	0.45 and above	6500
Acrocarpus fraxinifolius (FCRIAF-07)	0.45 and above	6000
B. Timber utility		
Tectona grandis (MTPTK-07, MTPTK-21,MTPTK-16)	0.60–0.73	16,000
	0.76–0.88	18,000
	0.91–1.21	25,000
	1.21 and above	38,000
Gmelina arborea (FCRIGA-08)	0.60–1.06	8500
	1.06 and above	12,000
Acacia hybrid	0.91–1.19	9200
	1.21 and above	12,000
C. Matchwood utility		
Ailanthus excelsa (MTPSS-07)	0.60 and above	6000
D. Pulpwood utility		
Casuarina equisetifolia	0.12–0.20	5500
Eucalyptus camaldulensis	0.12–0.40	4850
E. Biomass energy		
Subabul *(Leucaena leucocephala)*	0.05–0.40	3500
Other species	0.05–0.40	3500

This price supportive system has attracted several stakeholders towards establishing organized agroforestry
Source: Parthiban et al. (2021a, b)

24.5.3 Institutional Credit and Insurance Mechanism

The industrial agroforestry model introduced the concept of institutional credit and insurance mechanism to tree growing farmers. For this purpose, the scale of finance for more than 15 different tree species incorporated in agroforestry promotion have been established and extended to financial institutions to provide institutional credit to tree growers. Similarly, a comprehensive Tree Insurance Scheme (TIS) was implemented from 2013 onwards in association with United India Insurance, a public sector undertaking. The tree insurance scheme covers all perils and challenges faced by the farmers for seven promising farm growing tree species, viz., *Casuarina,* *Eucalyptus, Melia, Gmelina, Leucaena, Dalbergia* and *Ailanthus.* A premium of 1.25% of the input cost is charged for the purpose. This insurance mechanism is gaining attraction in the recent past (Parthiban 2016).

24.5.4 Suggesting Policy Issues

The consortium mode value chain system was involved in identification and documentation of various issues faced by farmers and other stakeholder, which demands policy level interventions. Hence, the consortium is actively involved in suggesting various policy issues like liberalizing timber transit rules, extending subsidy and providing drip irrigation facility to farm grown trees. The consortium has also suggested policy guidelines for implementing the national agroforestry policy in the state of Tamil Nadu (Parthiban et al. 2019). These activities are the key interventions in consumption or marketing levels.

24.5.5 Agroforestry-Based Carbon Finance

During the process of implementation of the model over a decade, it is learned that agroforestry needs to be financed for its carbon sequestration potential. For this purpose, one of the consortium members, viz., TIST who is involved in extending carbon-based financial benefits to tree growers. To further strengthen this, a wide range of deliberations and consultations are in the process with national and global institutions in order to design carbon credit model so as to benefit small holder agroforestry land use system.

24.6 Impact of Model

The programme has witnessed increased promotion of agroforestry and has created significant impact in terms of productivity and profitability besides ensuring a stable environment. Major impacts realized through this model are presented below.

24.6.1 Expansion of Area under Industrial Agroforestry

Implementation of the industrial agroforestry model over a decade has brought over 80,000 ha under organized industrial agroforestry plantations in association with pulpwood, plywood, timber and other c wood-based industries and is responsible for meeting at least 30% of organized raw material supply.

24.6.2 Impact on Productivity

Before implementation of value chain model, the productivity levels were less than 10 m^3 ha^{-1} $annum^{-1}$. After implementation of the model, the productivity level has increased to 25 m^3 ha^{-1} $annum^{-1}$ with a maximum recorded productivity of 50 m^3 ha^{-1} $annum^{-1}$.

24.6.3 Impact on Rotation

Before implementation of the value chain model, rotation followed for various tree species was more than 6 years. For certain tree species, there was a lack of organized felling period. After implementation of the model, the rotation/felling period has drastically reduced to as low as 18 months. For species like *Melia* (MTP 2), the rotation has been reduced to less than 2 years for use as raw material in the paper industries. In most cases, rotation has been fixed based on technical specifications in the form of girth of the tree which in turn has made a significant impact on promotion of agroforestry.

24.6.4 Economic Impact

The industrial agroforestry model has been characterized for its economic benefits. The financial analysis indicated that the benefit: cost ratio of industrial plantations exceeded 3:1 compared to baseline status thereby increased the profitability of tree growing farmers.

24.6.5 Social Impact

Promotion of value chain-based agroforestry plantations has ensured employment and income generation activities in the form of nursery establishment, pitting, plantation establishment, management, felling, conversion, loading, value addition and transportation. It is estimated that organized agroforestry development has created 300 man-days of employment per hectare in the entire production to consumption process. This approach is also able to create over 25 new business enterprises and has enhanced income generation activities through business incubator.

24.6.6 Environmental Impact

In terms of environmental impact, carbon sequestration potential was estimated at an average of 50 tonnes of carbon per hectare. It is estimated that the industrial agroforestry plantations established over a decade in association with various wood-based industries have sequestered more than four million tons of carbon and thus addressed the issues of climate change through clean development mechanism.

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References

Durairasu P, Parthiban KT (2013) Dendro biomass based power generation—A PCS (production to consumption system) approach in Tamil Nadu, India. Indian J Forest 36(1):31–40

FAO (2009) India forestry outlook study. Working Paper No. APFSOS II/WP/2009/06. Food and Agricultural Organisation, Ministry of Environment and Forests, Government of India (GoI)

Government of India (1980) Forest conservation act. Ministry of Environment and Forests, New Delhi

Government of India (1988) National Forest Policy. Ministry of Environment and Forests, New Delhi

Government of India (2014) National Agroforestry Policy. Ministry of Agriculture and Cooperation, New Delhi

Parthiban KT (2016) Industrial agroforestry: a successful value chain model in Tamil Nadu, India. In: Agroforestry research developments. Nova Science, New York, pp 523–537

Parthiban KT, Rao MG (2008) Pulpwood-based industrial agroforestry in Tamil Nadu—a case study. Indian Forester 134(2):155–163

Parthiban KT, Seenivasan R, Rao MG (2010) Contract tree farming in Tamil Nadu—a successful industrial farm forestry model. Indian Forester 136:187–197

Parthiban KT, Seenivasan R, Vennila S, Anbu PV, Kumar P, Saravanan V, Durairasu P (2011) Designing and augmenting pulpwood supply chain through contract tree farming. Indian J Ecol 38:41–47

Parthiban KT, Vennila S, Kumar P, Saravanan V, Subbulakshmi V (2014) Industrial agroforestry–a value chain approach in Tamil Nadu. In: Parthiban KT, Umarani R, Umesh Kanna S, Sekar I, Rajendran P, Durairasu P (eds) Industrial Agroforestry—perspectives and prospectives. Scientific Publishers, Jodhpur, pp 7–32

Parthiban KT, Sudhagar RJ, Fernandaz CC, Krishnakuman N (2019) Consortium of industrial agroforestry: an institutional mechanism for sustaining agroforestry in India. Curr Sci 117(1)
Parthiban KT, Krishnakumar N, Fernandaz CC (2020) Forest business incubator—an innovative institution for business development in forestry and agroforestry sector in India. Indian Forester 146:584–591
Parthiban KT, Fernandaz CC, Sudhagar RJ, Sekar I, Kanna SU, Rajendran P, Devanand PS, Vennila S, Krishna Kumar N (2021a) Industrial agroforestry—a sustainable value chain innovation through a consortium approach. Sustainability 13:7126
Parthiban KT, Srivastava D, Keerthika A (2021b) Design and development of multifunctional agroforestry for family farming. Curr Sci 120:27–28

Part V
Synthesis

Chapter 25
Synthesis: Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa

Gudeta Weldesemayat Sileshi, Sharda Rani Gupta, and Jagdish Chander Dagar

Abstract Over the last several decades, a large body of work has accumulated demonstrating that agroforestry could be instrumental in bringing stability and sustainability in agroecosystems and enable the transition towards a green economy. Agroforestry has also emerged as a potential tool to achieve some of the sustainable developmental goals set by the United Nations. The different chapters of this book have explored traditional and modern agroforestry practices in Africa and Asia. A key lesson emerging from the various chapters is that agroforestry can provide ecosystem services including provisioning, regulation and maintenance, and cultural services. The different chapters have also highlighted the challenges and barriers to wider adoption of various agroforestry practices, and identified how these barriers can be overcome to promote agroforestry as a mainstream land-use system. This chapter briefly synthesizes the key messages, the common challenges and the way forward. The implications for practice and policy of agroforestry involve investing in programmes at different scales for climate change mitigation and adaptation; biodiversity conservation and valuation of ecosystem services; addressing food and livelihood security of smallholders, women and resource poor farmers; emphasis on traditional and modern agroforestry for achieving the UN Sustainable Development goals.

Keywords UN Sustainable Development Goals · Synthesis · Traditional and modern agroforestry practices · Ecosystem services · Agroforestry business incubator

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25.1 Introduction

Integrating trees, crops and livestock through agroforestry arrangements has attracted increasing interest as an agroecological approach to sustainable intensification. For example, the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) identified agroforestry as a 'win–win' approach that balances the production of commodities with non-commodity outputs such as environmental protection and cultural and landscape amenities (Smith et al. 2012). Indeed, some experts argue that agroforestry is a model of sustainable intensification of agroecosystems (https://www.siani). Although sustainable intensification is a relatively simple concept, its implementation has remained elusive. This is partly due to the divergence in how 'intensification' has been appropriated to support different worldviews. Sustainable intensification is sometimes equated with the concept of 'agricultural intensification', which primarily focuses on maximizing productivity. Sustainable intensification originally focused on the need to move beyond the seed, fertilizer and pesticide technologies that supported conventional agriculture, towards more restorative production systems that rely less on external inputs and more on leveraging internal resources and ecological processes to supply nutrients and control pests (Pretty 1997). Over the years, the justification for sustainable intensification has expanded to address national and global concerns about agriculture's negative impact on environmental quality and natural resources on one hand, and the need to achieve substantial increases in productivity on existing farmland to avoid further loss of natural habitat on the other. Conventional agriculture is characterized as posing the greatest threat to biodiversity than any other human activity. It is also argued that success in conserving biodiversity and natural habitat requires good governance, appropriate legal frameworks for land tenure, and international agreements to ensure progress towards sustainable intensification (Garnett et al. 2013; Loos et al. 2014). Sustainable intensification is now recognized as one of the cornerstones of climate smart agriculture. In this book, sustainable intensification has been used with its broader definition and agroforestry is viewed as an agroecological and climate smart agricultural practice, and as an 'alternative' to conventional agriculture.

Agroforestry encompasses a wide range of systems practiced in diverse agroecological conditions and social-ecological contexts in an increasingly changing global climate. Asian and African countries have been experiencing unprecedent climate change, which is impacting agricultural production and livelihood options of people. Climate change has been predicted to have varying effects on the expression of land degradation, salinity, waterlogging and inundation in landscapes. As a result, there is a high degree of uncertainty regarding future ecological conditions of agroecosystems in which agroforestry interventions are being planned. This uncertainty is further increased by the interacting effects of climate, land use and demographic changes, which require adaptive management, namely, simultaneous learning and resource management in the face of uncertainty.

Over the last several decades a body of work has accumulated demonstrating that agroforestry could be instrumental in bringing stability and sustainability in agroecosystems and enable the transition towards a green economy. Agroforestry has also emerged as a potential tool to achieve some of the sustainable development goals set by the United Nations. The different chapters of this book have explored traditional and modern agroforestry practices in Africa and Asia. Some have shed light on advances in research and development and what has been learnt from traditional agroforestry practices to help develop modern systems. The information provided in the different chapters is hope to help in crafting supportive policies and incentives that promote agroforestry. This chapter will provide a synthesis of the salient findings, lessons and challenges identified in the different chapters to chart the way forward for future research and development.

25.2 Synthesis

A number of chapters in this compilation have documented the role that agroforestry can play in alleviating the challenges posed by climate change in Africa and Asia. The chapters have been classified into five parts each supporting the relevant information in a broad area of agroforestry knowledge. Part I has been devoted to 'Progress Towards Sustainable Intensification and Climate Change'. It has highlighted the growing interest in promoting agroforestry as part of sustainable intensification initiatives for the stability of agricultural production, and improving ecosystem services in the changed environment. It has been explored whether agroforestry can match the evolving climate change mitigation and adaptation agenda in Asia and Africa. It has also been argued that creating space for a continuum approach to agriculture, forestry and other land uses, within which trees outside forest and agroforestry can be recognized for what they are. It has been further emphasized that agroforestry can progress if efforts succeed to help farmers, corporate sectors and consumers to get better connected where products are exchanged for finance along a chain and formal government rules, rights and investment effectively connect all land uses, transcending current categorizations. The evidence for climate change mitigation and adaptation through farmer managed natural regeneration of trees in African drylands has been emphatically put-forth. The review on the subject has revealed active promotion of farmer managed natural regeneration of trees in the Sahel for over four decades, and currently to other regions in Africa and Asia. It has been further reported that this practice can contribute to carbon sequestration in plant biomass and soils while reducing greenhouse gas emissions. The opportunities to develop agroforestry practices in urban areas and dairy-based enterprises using treated municipal wastewaters for providing numerous services and safeguarding the environment in peri-urban areas have been identified. Here, it has also been argued that cities and other urban centres are hotspots of production, consumption and waste generation, including greenhouse gas emissions. Evidence has also been provided for the mitigation of climate change where urban agroforestry can be scaled up to city to regional levels. The importance of urban agroforestry was also felt during epidemic like Covid-19 when there was scarcity of consumable products especially vegetables, fruits and dairy products.

Over the years, evidence has been accumulating on the role of agroforestry in restoring degraded lands and desertification. This aspect has been broadly explored in Part II of this compilation. Here, different contributors have synthesized the existing evidence on the role of agroforestry in restoration of degraded land and ecosystem functions. The contributors have also demonstrated that agroforestry practices can provide other ecosystem services including provision of food, wood energy, improved soil fertility and enhancement of local climate conditions in degraded landscapes. The opportunities and challenges for integration of dryland agroforestry in large-scale restoration programmes such as the Great Green Wall initiatives to mitigate desertification have also been explored. It has been argued that the wider adoption of agroforestry may not only solve local land degradation problems but it can also help in tackling global health and environmental challenges caused by desertification. The urgent need for greater investment in agroforestry as a desertification mitigation measure was highlighted. In the drylands, livestock often form a major component of pastoral and agro-pastoral production systems, but communal lands are being overgrazed and degraded thus limiting the opportunities for pastoral communities. Here, it has been demonstrated that silvopastoral systems represent the main land uses for land reclamation and reducing-offset C emissions from soil by promoting the formation of soil organic matter and increasing SOC, enhancing soil quality, and improving ecosystem services like water and nutrient cycling. The key mechanisms responsible for soil organic matter, soil quality, and carbon emission offset have been identified. The opportunities for utilization of saline and other poor-quality waters in agroforestry to sustain production have also been explored. It has been further argued that biodrainage and phytoremediation techniques could be highly effective in recycling and reusing saline and poor-quality waters and reducing the soil contamination due to salts and other pollutants. Biodrainage, involving removal of excess soil water by deep-rooted fast-growing trees with high transpiration rate, is shown to be an appropriate method for managing waterlogging and its associated soil salinity. Several constraints in the use of saline and poor-quality waters for plantation and agroforestry programmes were also identified. The use of wastewater in irrigating forest plantation can create opportunities in the form of waste disposal to production. The dominant forms of temperate agroforestry systems in Nepal have been documented and the contribution of these systems to landscape restoration, climate change mitigation and disaster risk reduction have been highlighted and the key constraints to agroforestry promotion in Nepal including ambiguous policies, lack of institutions, market infrastructure and small landholdings are also provided.

In Part III, various contributors explored the role of agroforestry in biodiversity conservation in agricultural landscapes in Southeast Asia. Here the contributors synthesized evidence showing that agroforestry systems can increase the diversity of species and genetic resources due to the combination of crops, shrubs, and trees of different stand structure and strata increasing vertical diversity. A growing body of literature provides evidence that agroforestry trees provide critical habitats for wild animals including mammals, birds, reptiles, amphibia and invertebrates especially pollinators insects, soil fauna and flora. Evidence also abounds on the in-situ conservation of plant species. Asian and African countries are experiencing large scale biodiversity loss due to rapid conversion of forests to cropland, human settlement, infrastructure and industrial developments. This has brought also wildlife into conflict with humans. Substantive evidence that agroforestry systems can conserve species diversity and enhance ecosystem services has been provided. Careful agroforestry design will not only increase the multiple ecosystem functions, but also can create corridors and buffer zones to support natural habitats, and to reduce human and wildlife conflict. The role of agroforestry for plant diversity and livelihood security in different parts of Africa and Asia has been documented with an overview of the role of agroforestry in improving soil biodiversity, soil ecosystem functions and services, and litter decomposition processes. The diverse plant communities can modify the important soil functions, with possible feedback to the above- and below-ground components of both trees and crops. The documentary evidence that agroforestry systems are highly efficient in improving soil biodiversity and litter decomposition processes leading to increases in crop yields and sequestration of atmospheric carbon dioxide has been provided.

In Part IV of this compilation, contributors explored analytical frameworks for targeting agroforestry and policy perspectives to support scaling up and the use of geospatial information systems (GIS) for quantifying land potential and suitability mapping for agroforestry interventions. The authors argue that land suitability analysis and GIS can be harnessed for the planning and management of land and judicious application of agroforestry. In another chapter, the authors identified appropriate indicators and metrics for assessing climate smartness of agroforestry in terms of productivity, adaptation and mitigation benefits of the various frameworks. The degree to which agroforestry is represented in current Nationally Determined Contributions to the United Nations Framework Convention on Climate Change (UNFCCC), how its application is envisaged, and how its contribution could be enhanced, has also been explored. It has been shown that 80% of the non-Annex I countries could achieve their unconditional commitments by converting just about 25% of deforested areas to agroforestry. The potential of traditional agroforestry systems for intensification of agriculture and meeting the sustainable development goals (SDGs) with lessons from Asia and Africa has also been documented. A framework for analysing spatial patterns and extent of influence by single trees on ecosystem properties in agroforestry has been provided. It has been further shown that how PES can be used to incentivize farmers to preserve forest patches on their land through agroforestry interventions or converting degraded cropland into agroforestry systems. It has also been argued that poor institutional readiness and lack of mechanisms to reward farmers/land managers are among the critical issues that need to be addressed.

This compilation also provides a case study on the establishment of a consortium model and an institutional mechanism to create an agroforestry value chain for sustaining industrial raw materials. The chapter describes the creation of an agroforestry business incubator to leverage agroforestry business enterprise development in Tamil Nadu. The chapter also demonstrated that the value chain model has made significant impact in terms of increasing productivity, profitability, income and employment generation. The consortium was also involved in identification and documentation of various issues faced by farmers and other stakeholder, which demands policy level interventions. The potential of agroforestry as a source of industrial raw material and socio-economic impacts and related policy issues of adopting agroforestry by small land-holders have been explored. In total, the contribution addresses all the major aspects on potential of agroforestry for sustainable intensification of agriculture for meeting the challenges of mitigation of climate change and livelihood security, mainly in Asia and Africa.

25.3 Lessons and Challenges

A key lesson emerging from the various chapters is that agroforestry can provide ecosystem services including provisioning, regulation and maintenance, and cultural services. It is increasingly becoming clear that traditional and modern agroforestry practices adapted to local context can offer win-win solutions to the multiple environmental and societal challenges. This is because the various species play different roles, including improving soil health, production of fruit, timber, fuelwood, provision of shade and diversified habitats, income sources allowing alternative adaptation strategies. Nevertheless, the adoption of agroforestry has not been commensurate with its potentials and promises. The different chapters have also highlighted the challenges and barriers to wider adoption of agroforestry, and identified how these barriers can be overcome to promote agroforestry as a mainstream land-use system. In this section, we outline the common challenges and recommendations for research and development in the respective various chapters.

Many authors have identified either lack of national policy or lack of coordination among policy initiatives at different levels as constraints to scaling-up agroforestry. Experience in the Sahel has shown that where policies and incentives are favourable, farmers have adopted agroforestry practices suited to their circumstances. As a result, vast areas are now under tree cover through farmer assisted regeneration of trees in Senegal and Niger. Devising policy instruments that clarify land and tree tenure and carbon rights are specifically recommended and the policy bottlenecks need to be addressed at all levels. Land tenure is often cited as a fundamental bottleneck to tree planting especially in African countries where insecurity in land tenure limits the willingness of farmers to plant trees. The landless and the majority of women are often disadvantaged in terms of their ability to adopt agroforestry. Therefore, enabling policies and tenure rights are needed to address these challenges that underpin the low investment in agroforestry. Policy coherence also must be achieved at a number of levels, from international to local, to avoid conflicting rules and incentives. Experience from Latin America shows that good public policy can simultaneously address food and nutrition security, social inclusion and biodiversity-friendly agriculture by providing strong support to family farming that is closely linked to agroecological food production.

Lack of financial mechanisms and incentives as bottlenecks for scaling up agroforestry have been identified and further it is evident that without huge external investments, local and national governments may not have adequate financial resources to implementing large-scale initiatives. It has been argued for innovative and blended financing mechanisms, including blending mitigation and adaptation finance, to facilitate effective implementation of agroforestry practices. Blended financing implies the mixing of both public and private funds through a common investment scheme in a complementary way. It can also involve the strategic use of development finance and philanthropic funds in a catalytic way to mobilize private capital flows resulting in win-win for both investors and communities. It offers the possibility to scale up private sector investment for developing countries towards development impact.· Such financing is implied in the Paris Agreement and Africa's Agenda 2063. In addition, we strongly recommend governments and development agencies to explore the impact financing stream. This stream supports investment by private companies with aim to have a positive development impact at the base of the socio-economic pyramid, i.e., investment to have socioeconomic impact on rural livelihoods. In that regard, African and Asian countries are encouraged to approach development partners, private sectors and financial institutions that might be willing to support them to promote agroforestry to achieve the SDGs and meet their nationally determined contributions to the UNFCC. Financial institutions can play a role in using part of investment loan to countries to de-risk or leverage investments for development impact by the private sectors. This might offer opportunity to 'crowd in' private sector financing that would otherwise not be available to development interventions such as agroforestry.

Another key challenge is the dearth of information on the socio-ecological trade-offs and synergies in agroforestry options. Agroforestry systems are often characterized by trade-offs in terms of crop yields due to competition between trees and crops for nutrients, water and light. These trade-offs may be minimized with good management and well-informed choice of tree species. More investment is needed in research on the benefits and trade-offs to realize the full potential of agroforestry land use at local level. This needs decision support system for agroforestry development that is aligned with national strategies and policy scenarios. As demonstrated by authors, such a system would help planners and researchers in identification of agroforestry models suitable for various agroecological regions. There is also need for long-term studies to analyse the impact of different agroforestry practices for climate change mitigation and adaptation.

25.4 The Way Forward

It is evident that a major challenge to the world is to meet the food and nutritional security of the ever-increasing population. To meet that we would have to approximately double the food production over the next few decades that too in non-friendly environment. In recent past for achieving the targets of yield increases, the use of chemical inputs, genetic improvement, and mechanization has been unavoidable and become a conventional way of cultivation. This has further added to the woes of numerous social and environmental problems including increase in emissions of greenhouse gases hence climate change, land degradation, depletion in general ecosystem and biodiversity loss, scarcity of good-quality water, and disruption of social systems. There is a consensus that agricultural systems that ensure "multi-functionality" are needed to sustain land productivity (climate-smart agriculture) while increasing food production, simultaneously enhancing social and environmental goals, as committed to in the sustainable development goals (SDGs) of United Nations. Farming also needs to become more resilient to multiple insecurities including climate change, soil degradation, and market unpredictability, all of which reduce sustainability and are likely to exacerbate hunger. Therefore, agroforestry, is considered a problem-solving science not only in mitigating climate change but also for rehabilitation of all kinds of degraded lands, biodiversity conservation and food and nutritional security, especially in developing countries of Asia and Africa. As such agroforestry could enable countries the successful transitions towards a green economy and sustainable food systems.

For agroforestry to succeed on degraded landscapes, it requires a systems approach that can be readily integrated into landscape approaches, providing practicable solutions for food and livelihood security to the resource-poor farmers facing the challenge of climate change. For agroforestry in drylands, there is need to analyse climate change impacts on dust and sand storm activity; future projections of combined impacts of desertification and climate change on crop production, biodiversity and ecosystem services. Thus, the way forward is to bring the degraded lands under tree-based agricultural systems through relevant policy initiatives at national and regional level, and local level. Governments and institutions now have the opportunity to rebalance agricultural policy and investment towards such transitions. In doing so, they could achieve important improvements on multiple international commitments around the interlinked themes of food security, climate change, biodiversity conservation, and social well-being. Policies that institutionally segregate forest from agriculture miss opportunities for synergy at landscape scale. More explicit inclusion of agroforestry and the integration of agriculture and forestry agendas in global initiatives on climate change adaptation and mitigation can increase their effectiveness. Agroforestry as a land-use programme must be included as both an adaptation and mitigation strategy in the Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) by all the countries. By bringing more degraded landscapes under agroforestry can also contribute to greening the landscapes as has been illustrated by The Great Green Wall programme in Africa. The largest contributors to Greenhouse emissions have historically been energy, agriculture, industry and municipal waste. As discussed in this book, all these challenges can be addressed by adopting agroforestry through practicable policy initiatives with strong political will.

Through years of exposure to resource-degrading conventional agricultural practices, many soils in Africa and Asia are exhausted and now suffer from nutrient imbalances, deficiencies and low organic carbon concentrations. As a result, poor crop responses and low agronomic use efficiencies of applied nutrients are common. Agroforestry practices enhance soil organic carbon, while also allowing atmospheric nitrogen fixation and recycling of nutrients, together which help in improving the soil health. It is known fact now (as also discussed in this publication) that agrisilvopastoral systems help in sequestering more carbon followed by silvopastoral systems as compared to the sole systems of agriculture. Therefore, livestock-based agroforestry systems must have priority in dry ecologies and incentives bust be at place to adopt these systems. Similarly, in coastal areas plantation-based multi-enterprise systems may help not only increasing farmers' income many-fold but also will ensure protection from disasters like Tsunami, cyclones and intrusion of sea water.

Studies have shown that agroforestry systems generally have a favourable effect on the diversity of plants, and animals as well as improve soil biodiversity. The ecosystem services of agroforestry systems depend on plant, animal and microbial diversity, selection of suitable species combinations, and suitable management strategies under diverse environmental conditions. The agroforestry practices protecting indigenous species, genetic resources, cultural practices, threatened species as well as providing effective corridors for wildlife movement need to be promoted.

Delineation of the climatic zones in some countries like India has proved that more than 50% of coastal, humid and sub-humid and more than 30% of semi-arid areas are highly suitable for agroforestry. Most of the rain-fed areas can be brought under suitable tree-based systems establishing the trees using the saline aquifers, which are otherwise lying idle. To achieve the desired transitions we recommend: (1) the review and harmonization of policies, legal instruments and institutional frameworks to promote agroforestry; (2) supporting cross-country and cross-regional experience and knowledge sharing among institutions engaged in agroforestry research and development; (3) investment in research infrastructure and networks to foster collaborative agroforestry research; and (4) supporting communities in value addition and marketing of products and services from agroforestry.

References

Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HJC (2013) Sustainable intensification in agriculture: premises and policies. Science 341:33–34

Loos J, Abson DJ, Chappell MJ, Hanspach J, Mikulcak F, Tichit M, Fischer J (2014) Putting meaning back into "sustainable intensification". Front Ecol Environ 12:356–361

Pretty J (1997) The sustainable intensification of agriculture. Nat Res Forum 21:247–256

Smith J, Pearce B, Wolfe M (2012) A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renew Agric Food Syst 27:323–332

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