Jagdish Chander Dagar
Sharda Rani Gupta
Demel Teketay *Editors*

Agroforestry for Degraded Landscapes

Recent Advances and Emerging Challenges - Vol. 1

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Foreword

Agroforestry, historically, is as old as agriculture when domestication of both trees and herbaceous plants in the vicinity of each other was practiced by early humans in ancient times. Incidentally, there are several examples of forest and fruit trees mentioned in ancient literature throughout the world. Recognizing the ability of agroforestry systems to address multiple problems and deliver multiple benefits, most of the scientific achievements in agroforestry research developments took place only during the last three decades. Now, it is considered a problem-solving science and can both sequester carbon and produce a range of economic, environmental, and socioeconomic benefits. Approximately more than 1.2 billion people (about 20% of the world's population) depend directly on agroforestry practices, products, and services in rural and urban areas of developing countries. Adaptation to climate change is now inevitable, and research on agroforestry as an adaptation to climate change and as a buffer against climate variability is one of the priority areas of research. Traditionally, trees in agroforestry systems improve soil fertility through control of erosion, the maintenance of soil organic matter and physical properties, increased biological nitrogen fixation, extraction of nutrients from deep soil horizons, promotion of more closed nutrient cycling, and ameliorating micro-climate favorable for crop growth and increased biological production.

In recent years, agroforestry has developed as an autonomous science that aims at helping farmers to increase the productivity, profitability, and sustainability of their land. Keeping in view sustained productivity from the land, scientific efforts have been made to classify, understand, and improve agroforestry practices established over the centuries by the farmers' wisdom. Agroforestry can occur at a variety of spatial scales ranging from woodlot, farm, and watershed to the landscape in different regions of the world and cultures. Agroforestry provides approaches and technologies for mitigating the effects of harsh and erratic climatic conditions, restoring degraded ecosystems and landscapes, and enhancing soil fertility for sustainable production of food, feed, fuel, timber, fiber, medicines, and several other industrial products for the ever-increasing human population. Agroforestry is becoming increasingly important because of its multiple roles and services for biodiversity conservation, carbon sequestration, adaptation and mitigation of climate change, restoration of degraded ecosystems, and providing livelihood security to people.

The scientific information in the development of agroforestry technologies at various levels ranging from the farmers' field to the landscapes has grown significantly in recent years. In this pursuit, I am happy to note that Springer is going to bring out a book *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges* edited by JC Dagar, SR Gupta, and Demel Teketay, who have contributed in this field significantly. This assumes importance in the present scenario where every piece of land matters and restoration of degraded lands is a global priority, particularly in the developing countries. Agroforestry has to play a significant role in utilizing the degraded landscapes for sustaining agricultural production for livelihood and environmental security. This compilation presents a synthesis of studies and agroforestry approaches for degraded landscapes by renowned workers in their fields who have shared their knowledge and expertise to enrich this compilation. The editors have embarked on a wide range of topics dealing with agroforestry systems in tropical and temperate regions of the world.

I am sure this publication will serve as a useful reference book for researchers, students, and policy makers engaged in the pursuit of agroforestry research and development. The editors and the authors of the chapters of this book are to be congratulated for this significant contribution to the field of agroforestry.

M. S. Swaminathan Research Foundation
Chennai, India

M. S. Swaminathan

Preface

Agroforestry is widely recognized as a sustainable land-use management practice for different landscapes, both in tropical and temperate regions. Anecdotal agroforestry practices have been adopted worldwide since time immemorial as these have been evolved based on traditional knowledge of the natural resources. There are innumerable examples of traditional agroforestry systems involving combined production of livestock, trees, forages, and agricultural crops on the same unit of land across the world. As of today, the world's population has crossed 7.7 billion figures, and to meet the requirement of food and other commodities is a challenge keeping the resource sustainability intact. Globally, there is more than two billion hectares of degraded land providing opportunities for restoration to meet the socioeconomic needs of the ever-increasing human population and mitigating and adapting to the climate change. In this regard, agroforestry, which includes both traditional and modern land-use systems combining crops, trees, and livestock, is a promising land management system with significant economic, social, and environmental benefits. During the last four decades, agroforestry research, particularly in degraded landscapes, has gone a long way to attract the attention of researchers, primarily as a means of improving biodiversity, enhancing ecosystem services and carbon sequestration, sustaining agricultural productivity, limiting the impacts of anthropogenic climate change, as well as maintaining economic growth and social structure.

In the recent past, however, given the prevailing scenarios of climate change, there is a paradigm shift toward environmental protection, and sustainable land use is being considered all over the different regions while tree-based systems are being promoted globally. Due attention is being given by different governments on increasing tree cover on agricultural lands. The formulation of "National Agroforestry Policy 2014" by India is an example of the importance being given to the discipline of agroforestry.

In this book, an attempt has been made to present different aspects of agroforestry research development on degraded landscapes. Now, agroforestry is being considered not only for sustainable agricultural productivity, but also as problem-solving science, such as control of erosion, sand dunes stabilization, alternate to shifting cultivation, controlling seepage and waterlogging along canals, protecting seashores from the vagaries of cyclones and tsunamis, and mitigating climate change through tree-based smart agricultural interventions. In view of new challenges for restoring degraded landscapes and to develop future strategies to move forward, it is essential to evaluate the past and present status of research in the field of agroforestry on degraded landscapes. Therefore, we invited contributions from eminent researchers with keen interest in agroforestry and forest landscape restoration to submit manuscripts for peer review. After going through a rigorous peer review process, 34 book chapters (including the last one on synthesis of all the chapters) have been selected for inclusion in this book. The manuscripts represent original research and synthesis work that deals with the different aspects of agroforestry systems developed for degraded environments in tropical and temperate regions of the world, which have been grouped into two volumes of the book each containing three parts and 17 chapters.

In Volume I, the introductory part (Chaps. 1 and 2) deals with the scope and importance of agroforestry for degraded landscapes and for improving environmental services. An overview of agroforestry as a tool for rehabilitation of degraded landscapes discusses the extent of land and ecosystem degradation, ecological restoration of degraded landscapes, and agroforestry systems for livelihood and environmental security. The second part contains eight chapters that explore various aspects of the tropical agroforestry systems of arid and semiarid regions, and the third part (seven chapters) deals with humid and subhumid regions of the world. Various aspects of agroforestry systems such as traditional practices, advanced research trends, emerging challenges, and potentials of agroforestry rehabilitation of degraded landscapes achieving livelihood and environmental security in arid, semiarid, subhumid, and humid regions have been dealt with. Land-use management by small holders as a promising way for synergies between Rio Convention has been explained. Further, importance of agroforestry for improving nutrient cycling and soil fertility through leguminous fertilizer trees in degraded soils has been emphasized.

In Volume II, four chapters in the fourth part explore the sustainability indicators and soil quality parameters for long-term sustainable production and restoration of temperate agroforestry systems. Biomass production, improvement of rangelands, and gradual recovery of *Nothofagus* forests through agroforestry interventions have been discussed. The twelve chapters included in Part V bring together a broad range of agroforestry interventions for protection of soil from erosion, rehabilitation of saline lands and checking water logging/seepage, utilization of waste/sewage water, and tree-based systems for mine spoils. In this part, emphasis has been given to the role of some important trees in sustainability of the system, soil fertility, carbon sequestration, climate change mitigation and adaptation, and socioeconomic well-being. In the last part, a chapter has been added on synthesis explaining the theme and epilogue of the entire book.

Specific problems have been discussed by the experts who have been working in the field of agroforestry with a focus on degraded landscapes for quite a long time and have added their field experiences to the value of this book which will, certainly, prove quite useful for different stakeholders, including, but not limited to, farmers, national, regional, continental, and international scientists, researchers, educators, students, development/extension agents, environmentalists, policy/decision makers, and government and nongovernment organizations as well as national, regional, continental, and international communities, including business people and organizations, interested in agroforestry. A synthesis of the important observations made in the text has been done in the last chapter for a holistic view of this important publication.

We thank the contributing authors for their long and continued commitment in helping us with the successful completion of this document. The invaluable comments and suggestions made by the reviewers also significantly improved the clarity and content of the chapters. We are grateful to the large number of individuals, organizations, and academic institutions whose research publications, technical reports, and annual reports provided the much-needed information to the respective chapter authors of this book. Last but not least, we are highly indebted to Professor MS Swaminathan, Founder Chairman MS Swaminathan Research Foundation and Former Member of Parliament (Rajya Sabha), for writing a foreword to this book.

New Delhi, India — Jagdish Chander Dagar
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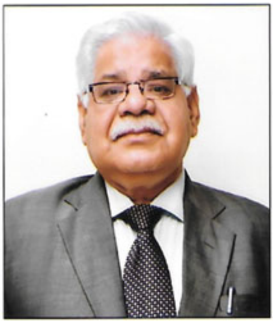

Jagdish Chander Dagar, Former Assistant Director General and Emeritus Scientist at ICAR, has long been actively involved in the areas of agroforestry, natural resource management, biosaline agriculture, rehabilitation of degraded lands, ethnobotany, plant ecology, environmental sciences, biodiversity, climate change and sustainable agriculture, as can be seen in his more than 300 research papers, published in peer-reviewed journals, book chapters and conference proceedings. He has been conferred with several awards and honours and is a Fellow of the National Academy of Agricultural Sciences and several other professional societies. He has also been a consultant to the UN, CIMMYT, and Haryana Forest Department. Dr Dagar is also Chief Editor of the Journal Soil Salinity & Water Quality.

Sharda Rani Gupta, Former Professor of Botany, Dean of Life Sciences, and Emeritus Fellow of the UGC, is a nationally and internationally recognised ecologist who has taught at the Department of Botany and at the Institute of Environmental Studies at Kurukshetra University, India. She has made significant contributions to better understanding the biodiversity and ecosystem functions of grasslands, forest ecosystems, soil biodiversity, ecological rehabilitation of salt-affected soils, carbon sequestration in agroforestry systems, and the sustainability of conservation agricultural systems. The author of 98 research papers published in national and international journals, she is also a Fellow of the National Institute of Ecology and is affiliated with the Institute of Environmental Studies.

Demel Teketay received his MSc in Plant Taxonomy from Reading University (UK) and PhD in Forest Vegetation Ecology from the Swedish University of Agricultural Sciences. He is currently serving as a Professor of Forest Sciences and founding Dean of the Faculty of Natural Resources at Botswana University of Agriculture and Natural Resources (BUAN). He has published over 250 scientific articles and technical reports, including more than 150 peer-reviewed articles in national and international scientific journals. He is a Fellow of The World Academy of Sciences (TWAS), International Fellow of the Royal Swedish Academy of Agriculture and Forestry (RSLA), Fellow of the African Academy of Sciences (AAS), Associate Fellow of the Ethiopian Academy of Sciences (EAS), and a Member of the Botswana Academy of Science (BAS).

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Part I

Introductory

Introduction

1

Jagdish Chander Dagar, Sharda Rani Gupta, and Demel Teketay

Abstract

Agroforestry is now considered an effective land use system, which contributes to food, nutritional and environmental security, and has great potential to restore degraded landscapes. There are different forms of land degradation, such as inappropriate land use and management, deforestation and forest degradation, loss of biodiversity, soil erosion, salinization, acidification, waterlogging, desertification and mining in different regions of the world. To meet the socio-economic needs of the ever-increasing human population as well as mitigate and adapt to the prevailing climate change, there is a need to restore or rehabilitate all kinds of degraded lands. The agricultural systems need fertile land for optimum production, but agroforestry systems have unique characteristics that provide livelihood security besides providing food, fodder, fuel, timber and several other products from the degraded lands. Agroforestry, as subject of scientific investigation, assumes wider recognition in view of the need to maximize biological productivity based on sustainable land management. 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 productivity of degraded lands besides conserving biodiversity and enhancing environmental services. Research efforts have shown that most of the degraded

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areas prone to soil erosion, salinization, waterlogging and mining and coastal mangrove areas can be made productive by adopting suitable agroforestry practices and techniques. The possibilities are developing plantation-based cropping systems, using fertilizer trees in dry lands and integrating high-value medicinal and aromatic plants, livestock, poultry, forest and fruit trees and vegetables in agroforestry. This introductory chapter discusses in brief agroforestry practices and technologies for degraded landscapes and their service functions with a focus on biomass production, sustainability indicators, carbon sequestration, soil fertility improvement, biodiversity conservation, ecosystem services and climate change mitigation. The implementation of agroforestry technologies as a practicable tool for restoring degraded landscapes and climate-smart agriculture is needed in restoration policies, strategies, national plans, programmes and projects.

Keywords

Land degradation · Agroforestry systems · Environmental services · Soil erosion control · Fertilizer trees · Soil fertility · Carbon sequestration · Biodiversity · Ecosystem services · Policy issues

1.1 Background

The global human population is increasing unabated worldwide, currently estimated at nearly 7.7 billion and projected to increase to 8.6 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100 (UN 2017, 2019). The increasing population is aggravating the need for more productive and sustainable use of our land resources. The population increase coupled with current environmental degradation that has resulted from past and ongoing unsustainable land use practices implies that there is an urgent need for changing the way we manage our lands as well as the ecosystem services from trees on farms and in agricultural landscapes. In this regard, agroforestry, which includes both traditional and modern land use systems combining crops, trees and livestock, is a promising land management system that can have significant economic, social and environmental benefits. Therefore, agroforestry systems can provide a sustainable alternative to low-diversity cropping systems. Agroforestry offers a unique set of opportunities to restore degraded lands for agricultural use, providing ecosystem services and enhancing the multifunctionality of landscapes (Nair 2007; Hillbrand et al. 2017; Park et al. 2018). The tree and soil components in agroforestry systems can sequester carbon for medium to long term, thereby contributing to climate change mitigation. Agroforestry systems have been found to be environmentally friendly practices and cost-effective strategies of land management for forest landscape restoration (Oliveira and Carvalhaes 2016; Hillbrand et al. 2017).

Although the practice of combining crops, forest and fruit trees and domestic animals on the same unit of land in sequential or temporal dimension has existed for thousands of years throughout the world, agroforestry as a science has a recent origin, and the term “Agroforestry” is just about 40 years old. The need for recognizing the term “Agroforestry” emerged when it became clear that the treatment of agriculture and forestry as separate sectors and domains of policy, and the collection of statistics with a firewall between them, did not match the reality on the ground (van Noordwijk et al. 2016). Earlier, the agroforestry practices focused on the plot-level practice of combining trees with other farming components including animals. After creating a typology of the many forms of existing agroforestry practices (Nair 1985, 1993), emphasis shifted to tree–soil–crop interactions, the microclimatic effects of trees, bioeconomic trade-offs and management options using biodiversity to reduce the risks (see Batish et al. 2007; Dagar and Tewari 2017; Udawatta et al. 2017; Catacutan et al. 2017). It is true that many of the anecdotal agroforestry practices, which are time tested and evolved through traditional indigenous knowledge, are still being followed in different regions of the world. At the same time, the traditional knowledge and the underlying ecological principles concerning indigenous agroforestry systems around the world have been successfully used in designing the modern agroforestry systems. Many of them such as improved fallows, alley cropping, homegardens and park systems evolved based on the modern, science-based approach so as to harness the sustainability attributes and production benefits of such time-tested practices (Dagar and Tewari 2017). AGFORWARD project has played an important role in advancing the understanding of the extent of agroforestry in Europe and of farmers’ perceptions of agroforestry; the biophysical and economic models have been developed to predict the effect of different agroforestry designs on crop and on carbon sequestration, nutrient loss and ecosystems services (Burgess and Rosati 2018).

A second, broader concept of agroforestry emerged with a focus on different aspects of the agriculture–forest interface, the landscape-level interactions in multifunctional landscapes, trees outside forests and farmers/communities actively involved in (institutional) forests (Catacutan et al. 2017). Tenure, rights, conflicts and migration became part of the agenda, as did the ecosystem services related to the flows of water and movement of flora and fauna in the landscape as a basis of agrobiodiversity change. It became increasingly clear that maintaining biodiversity and ecosystem services, managing agricultural production sustainably and improving rural livelihoods cannot be achieved at just the farm or plot level, but are linked at the landscape scale (Dewees et al. 2011). For example, in drylands of Africa, woodland and woodland mosaics provide valuable inputs into farming systems, including leaf litter for cropping systems and livestock browse and fodder. In Southeast Asia, forest landscapes occurring in rural farming systems enable people to exploit mountain slopes in ways that yield a diversity of crops, maintain soil fertility and watershed functions and retain indigenous biodiversity.

Forest and landscape restoration is the process of reversing the degradation of soils, agricultural areas, forests and watersheds, thereby regaining their ecological functionality. Forest and landscape restoration has come of age striving to restore the lost and degraded forests and their surrounding landscapes in different regions of the world. Forest landscape restoration (FLR) encompasses a wide array of activities that have been categorized in the Restoration Opportunities Assessment Methodology (ROAM) (IUCN and WRI 2014). The world of opportunity map of landscape restoration indicated that, globally, there was more than two billion ha of degraded land providing opportunities for restoration (IUCN and WRI 2014). Furthermore, it has become increasingly evident that drivers of change form the basis for "theories of change," including low-emission development options and "green growth" (Catacutan et al. 2017). Agroforestry FLR has a focus on integrating trees in an agricultural landscape composed of crops and/or livestock (Hanson et al. 2015). For example, the land uses range 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 restoration pathways for highly degraded ecosystems soils with very low soil fertility or that are prone to erosion.

This introductory chapter examines in brief the potential of agroforestry systems to provide environmental services on degraded lands, agroforestry as a problem-solving science and the relevance of agroforestry for degraded landscapes.

1.2 Land Degradation

Land degradation is the persistent reduction of the capacity of the land to support biodiversity, ecosystem services and human needs. This creates conditions of reduced food production, water storage, biodiversity, and carbon sequestration in the soil–plant system (IUCN 2015; Laban et al. 2018). The Economics of Land Degradation (ELD) initiative estimates the cost of lost ecosystem services due to land degradation ranges from 6.3 to 10.6 trillion US$ per year, which is equivalent to 10–17% of global GDP (ELD 2015).

Estimates of the extent of land degradation are highly variable due to divergent definitions of degradation and varied approaches being used for estimating land degradation (Gibbs and Salmon 2015; IUCN 2015). The estimates indicate that 25% of the world's lands are either highly degraded or subject to high rates of degradation (FAO 2011; FAO and ITPS 2015). In Africa, 65% of arable land, 30% of grazing land and 20% of forests are degraded. Asia can be divided into several climate zones: tropical and subtropical in South Asia, humid subtropical and temperate in East Asia, semi-arid in China and arid in Mongolia and East Asia. Most regions of Asia are affected by the Asian–Australian monsoon which causes dry and wet seasons. Water erosion is the major type of erosion in the regions of South and East Asia with alternating dry and wet seasons. On the other hand, wind is the key driving force inducing soil erosion in the drier and desert areas. In the semi-arid and arid zones of Central and West Asia, salt-affected soils are widely distributed (Toderich et al. 2013). In India, 29.3% of the geographical area of the country has undergone land degradation due to inappropriate land use and management, soil erosion, salinization, acidification, waterlogging, desertification and mining (ISRO 2018; www.sac.gov.in).

In Latin America and the Caribbean, water erosion and landslides are prominent threats in the sloping lands of the mountains, especially when the slopes have been burned and overgrazed (FAO and ITPS 2015). In semi-arid and arid areas, salinity and sodicity are important threats to soil; nearly one billion ha of land is impacted by salinity representing about 7% of land area globally (Wicke et al. 2011).

Processes of land degradation are those direct mechanisms by which land is degraded. A number of interactive physical, chemical, biological and human processes have led to land degradation (Johnson and Lewis 2007). The most widespread and studied land degradation processes affecting soils are water and wind erosion, which have accompanied expansion of agriculture in different regions of the world. Other physical degradation processes include soil compaction, hardening and sealing and any other mechanism leading to the loss of porous space crucial for holding and exchanging air and water (Hamza and Anderson 2005). Natural acidification is a common process in the soils of Latin American countries and is very intense in tropical areas of the region, because of the high rainfall. Anthropogenic acidification in soil could also appear because of excessive N-fertilization on crops like banana, vegetables and oil palm and under intensive coffee systems (see FAO and ITPS 2015). Salty soils occur naturally under dry to subhumid climates (primary salinity); human interventions have expanded their distribution (secondary salinity with irrigation without proper drainage being the predominant cause of salinization) (Rengasamy 2006).

Global soils store more carbon as compared to the amount of carbon stored in phytomass and the atmosphere (Scharlemann et al. 2014). Loss of soil carbon, mostly, occurs after deforestation and intensive cultivation of grasslands and monoculture. Vegetation clearing processes are associated with land use changes through deforestation as well as conversion of grasslands, dry steppes and shrublands to croplands, pastures, urbanization or just barren land. This clearing process is associated with net carbon losses from the vegetation and soil carbon pool. The soil organic matter pools have diminished not only in cultivated land but also under natural vegetation; climate-driven losses of soil carbon are currently occurring across many ecosystems at global scale (Bond-Lamberty et al. 2018). For example, land use changes from forestry to urban or livestock use cause the greatest loss of soil carbon in Latin American countries (Lal 2005, 2006).

1.3 Agroforestry Systems and Their Service Functions

The multitude of agroforestry systems that have evolved over long periods in a variety of ecologies reflect the accrued wisdom and adaptation strategies of millions of farmers, particularly smallholders, to meet their basic needs of food, nutrition, fodder, fuelwood, plant-derived medicines and cash income. In the process, several agroforestry systems/practices have come in existence, and many of them are now seen as problem-solving technologies. The underlying principles and traditional knowledge concerning indigenous agroforestry systems around the world have been used successfully in the design of improved systems (Nair 1993; Nair et al. 2016; Dagar and Tewari 2017). The types of agroforestry systems are complex and diverse both in tropical and temperate regions of the world and exhibit great diversity in spatial, temporal and sociocultural dimensions. Nair et al. (2016) presented a qualitative SWOT (strengths–weaknesses–opportunities–threats) analysis of unique agroforestry systems and showed several common attributes among them in terms of production, environmental and sociocultural attributes. This study also indicated that sustainability, multifunctionality and high sociocultural values are the common strengths, whereas low levels of production and lack of systematic research and technological inputs to improve the systems are the major weaknesses (Nair et al. 2016). Recognizing the role of agroforestry in climate-smart agriculture and landscape management by the communities, agroforestry options could suggest models for sustainable development.

Agroforestry is not restricted to farmland, but is also amenable to improve rangelands, eroded areas and degraded landscapes. For example, in the arid regions of Rajasthan in India, agroforestry systems with *Prosopis cineraria* and *Ziziphus nummularia* have been developed in combination with runoff farming under the name of "khadin" farming. In this type of farming, rain water is collected on an uncultivated catchment area and driven to a nearby lower farmed area where it is kept percolating through small banks (Tewari and Dagar 2017). A similar system ("meskat") is used for maintaining arid land olive tree groves in Northern Africa.

Soil erosion has socio-economic, environmental and technical dimensions. A more beneficial alternative for eroded landscapes, both in high rainfall and semi-arid regions of the world, is to create multifunctional land use systems. For example, shrubs like *Gliricidia sepium*, *Leucaena leucocephala*, *Cassia siamea*, *Cajanus cajan* and *Sesbania sesban* are planted (usually in paired rows) across the slope, and crops like millets or forages are cultivated in interspaces between the hedgerows. These nitrogen-fixing shrubs are pruned regularly at about one meter height for fodder or mulch (twigs used as fuelwood) and help in checking soil erosion and ameliorate the soil by fixing the nitrogen and through litter or when used as mulch, in that case conserve in situ moisture (Sileshi et al. 2014; Dagar et al. 2014a). Further, native trees can be planted together with shade-tolerant agricultural cash crops, such as coffee, cocoa, cardamom, zinger or turmeric, or medicinal plants cultivated on degraded forest lands in southern India (Elevitch et al. 2018). Windbreaks and shelterbelts are known to have beneficial effects on agricultural production throughout the world (Tewari et al. 2014).

Agroforestry systems are helpful in maintaining soil productivity at optimum levels over a long period of time, when compared with agricultural crops alone, because the leguminous trees used in agroforestry systems fix nitrogen. Use of fertilizer trees, along with arable crops, in dry regions of Africa to enhance crop productivity and ameliorate soil is quite popular (Akinnifesi et al. 2010; Sileshi et al. 2014). Nitrogen-fixing trees enhance crop productivity manyfold in dry regions. Combining agricultural crops with trees helps in increasing the productivity of the land. Higher yields of crops have been observed in tree-influenced soils than in soils not supporting trees (Sileshi et al. 2014; Tewari et al. 2014).

Most agroforestry systems constitute sustainable land use and help to improve soils in a number of ways. Some of these beneficial effects are apparent in experiments carried out in different parts of the world (Nair 1993; Young 1989; Dagar et al. 2014a; Dagar and Tewari 2017). Tree crowns protect the soil from the impact of raindrops and create a specific microclimate in the particular area. Frequent droughts and failure of crops is characteristic of arid regions. There is high risk in raising soil management standards or increasing inputs even in the form of fertilizers, manures and micronutrients in arable farming even on good agricultural lands in arid regions. This is because of the uncertainty and often erratic nature of rainfall. Crop yields in the arid region are low, and there is a large fluctuation in yield from year to year. Agroforestry can, therefore, provide economic viability in the years when rainfall fails.

It has been now well established that agroforestry provides environmental services through erosion control, carbon sequestration, bio-drainage, soil improvement, biodiversity conservation (including soil microbial diversity) and climate change mitigation. Soil improvement in agroforestry systems is linked to various soil biological processes like nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, building up soil organic matter from aboveground and belowground parts of plants, increasing soil microbial activity, improving soil enzyme activity and enhancing activity of arbuscular mycorrhizal fungi (see Dollinger and Jose 2018 and references cited therein).

Agroforestry can increase biodiversity on degraded lands by enhancing numerous ecological and production functions and improves regulatory ecosystem services, including erosion control, nutrient retention, water quality, soil health, air quality, pollination, pest control and cultural services (Torralba et al. 2016; Rey Benayas and Bullock 2012). Agroforestry can significantly improve ecosystem services (ES) and enhance biodiversity conservation on degraded agricultural land and deforested areas (Chazdon 2008; Coelho 2017). Only a few studies have quantified the effectiveness of agroforestry systems to recover biodiversity and provision of ecosystem services in degraded areas (Santos et al. 2019; Torralba et al. 2016; Shimamoto et al. 2018). In a meta-analysis conducted in Europe, agroforestry systems showed a significant positive effect on biodiversity conservation and ES provision when compared with conventional systems, specifically in relation to nutrient cycling, biodiversity conservation and erosion control (Torralba et al. 2016). There is a close relationship between agroforestry and biodiversity conservation because of change in focus from the traditional tree-based land use practice to more advanced landscape-scale agroforestry approach (McNeely and Schroth 2006; Torralba et al. 2016; Udawatta et al. 2019).

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). This has been achieved by reconciling agricultural production and biodiversity conservation or enhancement at the landscape level (Rey Benayas and Bullock 2012). Agroforestry has become a part of a climate change response by adapting to increased risks and uncertainties, facilitating capturing and storing of carbon, and restoring landscape multifunctionality to allow current human resource appropriation to become sustainable (van Noordwijk 2018; Catacutan et al. 2017).

1.4 Emerging Challenges and Agroforestry as a Problem-Solving Science

Agroforestry has a potential for driving sustainable rural development; however, agroforestry continues to face scientific, policy and institutional challenges for its wider adoption by the farmers and land managers in multifunctional landscapes. In the modern scenario, it is well known that the impacts of climate change are eminent, which necessitates appropriate adaptation and mitigation measures, on a priority basis. The developing countries like India and those in Africa are more vulnerable to climate change in view of large population being dependent on agriculture and natural resources. The warming trends over the last two decades are likely to further aggravate the situation and create new challenges for food production. The decline in agricultural productivity, rise in sea level and frequent occurrences of climate-related disasters are of great concern. Related issues such as losses of biodiversity, degradation of natural resource base, competing demands, abiotic stresses, emerging pests and diseases, ecosystem degradation and nature's ability to supply nutritious food are some other challenges in this fast-developing field of agroforestry. The UN Sustainable Development Goals are dependent on conserving biodiversity and limiting climate change. It remains a challenge to develop the economic instruments based on ecosystem services for greater adoptability of agroforestry for sustainable utilization of degraded landscapes and providing livelihood opportunities to the local people.

In view of growing human population, it is also a major challenge to ensure nutritional security for over a billion people and to tackle the problems of widespread hunger and malnutrition. Irrigated agriculture is facing new challenges of lowering of water tables due to excess groundwater pumping and waterlogging and salinity in canal command areas. Because of these reasons and shrinking landholding, the agricultural growth and economy are deteriorating, and farmers' livelihood is at risk.

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 the second-generation problems, such as secondary salinization due to waterlogging and contamination of water resources due to use of excess nitrogen fertilizers and pesticides. In most of the urban and semiurban areas, greenery is established or landscapes are developed as recreation parks using semi-treated sewage water (Borelli et al. 2017; Dagar and Yadav 2017). Agroforestry-based technologies have been developed to rehabilitate sodic and saline waterlogged areas (Dagar et al. 2016a, b), highly eroded ravine lands (Dagar and Singh 2018), mine spoil areas (Chaturvedi et al. 2014), sand dunes stabilization (Tewari et al. 2014) and use of poor-quality waters in agroforestry (Dagar and Minhas 2016). Agroforestry practices, along with domestication of fruit trees, are the major features of the land use systems in the drylands of Eastern, Central and Southern Africa (Jama and Zeila 2005; Leakey et al. 2012; Akinnifesi et al. 2008, 2010; Kitalyi et al. 2010; Wekesa and Jönsson 2014; Sida et al. 2018; Agroforestry Network and Vi-skogen 2018). Towards landscape management, agroforestry plays an important role in reducing greenhouse gas emissions (Amadi et al.

2016; Kim et al. 2016; Baah-Acheamfour et al. 2017) and mitigating climate change (Catacutan et al. 2017).

The entire world is looking towards agroforestry-based agriculture to sustain crop productivity and mitigate climate change. The role of mangroves in stabilizing coasts and during frequent events of cyclones and tsunamis is well established. New concepts, such as integrated farming systems, domestication of high-value native plants and urban and peri-urban agroforestry, have emerged. 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. Many of these topics, especially related to degraded landscapes, have been included in this publication.

1.5 Relevance of Agroforestry for Degraded Landscapes

During the last few decades, agroforestry research, particularly in degraded landscapes, has gone a long way. The results of a survey by ICRAF revealed that almost half of all farmed land in the world has more than 10% tree cover; thus, nearly 1.0 to 1.2 billion ha of agricultural landscapes now have trees on them (Garrity 2012; Zomer et al. 2016). In some regions, such as Southeast Asia and Central America, tree cover on farms exceeds 30%. Forest transitions are now occurring in a large number of countries in both the tropical and temperate zones. As discussed above, tree planting techniques have been developed for afforestation of highly alkali soils and waterlogged saline soils. Watershed-based agroforestry systems have been developed to check soil erosion and increase crop productivity. Farmers are gaining good economic returns from improved homegardens and improved fallows. Many of these results have been documented in chapters on biodiversity conservation as well as traditional and modern agroforestry systems as an alternative to shifting cultivation.

Agroforestry affects socio-economic and ecological parameters in different spatial, temporal and institutional dimensions. The majority of the agroforestry research has focused on biophysical parameters at the farm level. Landscape-level research undertakings are few because of the complexity of landscape, the long-time series of data needed to study economic and social impacts and the lack of baseline studies on levels larger than the farm. A remarkable return of trees to the landscapes of Southern Niger has been well documented and analyzed, with more than five million hectares in the Maradi and Zinder regions of Niger regreening project (Sendzimir et al. 2011). The success of this restoration project was due to multiple actors, institutions and processes operating at different levels and temporal and spatial scales to initiate and sustain the reforestation trends (van Noordwijk et al. 2016). In recent years, researchers and organizations have focused on more studies at landscape levels, including socio-economic aspects (Nair et al. 2009; Akinnifesi et al. 2010; Kuyah et al. 2016; Reed et al. 2017). The agroforestry systems, especially biodiverse systems, can be used for recovery of degraded landscapes and adopted as a more environmentally friendly land management practice

(Montagnini 2017; Santos et al. 2019). Implementation on a large scale would be easier if specific environmental public policies existed (FAO 2013) and research efforts focused on more inclusive agroforestry research (Coe et al. 2014).

Multilayered plantation-based agroforestry systems, homegardens, alley cropping on sloping land, tree-based fodder banks, fodder cultivation beneath coconut plantations, integrated farming systems, mangrove-based aquaculture, farming in forests and nitrogen-fixing and other multipurpose trees on farm boundaries are some interesting agroforestry systems suitable for coastal and island situations, which will not only restore these ecosystems and sustain livelihood and nutrition security but also render ecological services, such as biodiversity improvement, carbon sequestration and mitigate climate change (Dagar et al. 2014b).

Agroforestry systems have the potential to restore degraded lands, support livelihoods, improve food and nutrition security and reduce poverty, but constraints limit the adoption of these land use systems in landscape restoration initiatives (Hillbrand et al. 2017). The various policy initiatives to stimulate the scaling up of agroforestry in landscape restoration must have a focus on (1) greater recognition of agroforestry systems as practicable options for restoring degraded landscapes in restoration plans and policies; (2) enabling policy environments for the development and scaling up of traditional and improved agroforestry systems in landscape restoration projects; (3) implementing incentive schemes based on the role of trees in providing ecosystem services, such as erosion control, enhanced biodiversity, water quality and carbon sequestration; and (4) defining risk-mitigation mechanisms to attract more investment in agroforestry (Hillbrand et al. 2017). Furthermore, agroforestry helps to provide opportunities to meet the livelihood security of poor and landless farmers and mitigate climate change and several other ecological service functions.

1.6 Outline of the Book

There has been a tremendous growth in the number of publications on agroforestry systems in the recent past. Agroforestry technologies have been applied to rehabilitate or restore degraded lands from agriculture, soil erosion, deforestation, rangeland degradation, mining sites and overextraction at various scales, from plot to farm levels to large agricultural and farming enterprises. Hence, the objective of this book is to bring together a collection of original research and review articles that deal with the different aspects of agroforestry for degraded lands from both the tropical and temperate regions of the world. We have highlighted the chapters included in this publication in the following paragraphs.

The Volume 1 of this book has three parts which include introductory, tropical and sub-tropical systems in arid and semi-arid regions, and humid and sub-humid regions. In Part I, Dagar et al. in the introductory Chap. 1 examine in brief the potential of agroforestry systems to provide environmental services on degraded lands, agroforestry as a problem-solving science, the relevance of agroforestry for degraded landscapes and the challenges for implementing agroforestry for forest and landscape restoration. Gupta et al. in Chap. 2 have discussed the global extent of land and ecosystem degradation, forest landscape restoration, agroforestry systems suitable for degraded landscapes and the potential of agroforestry systems to provide environmental services, including erosion control, enhanced biodiversity and ecosystem servicers, improvement of soil fertility and climate change mitigation.

The eight chapters (Chaps. 3–10) included in Part II emphasize that tropical agroforestry practices are major features of the land use systems in the arid and semi-arid regions. Dagar et al. (Chap. 3) have dealt with the advances in agroforestry research, describing traditional and improved agroforestry systems practised in African continent. A detailed account of agroforestry for soil conservation and amelioration, domestication of indigenous fruit trees, their transformation and marketing, research opportunities and policy initiatives have been presented. Kuyah et al. (Chap. 4) described the main tree-based systems that are widely practised in sub-Saharan Africa based on an extensive review and explained that agroforestry systems are typically multifunctional in the landscape and support sustainable livelihoods for food production, health and nutrition, wood-based energy and income. These workers discussed some case studies and highlighted gaps in knowledge and barriers to developing agroforestry-based livelihoods. Shiran et al. (Chap. 5) have described agroforestry systems for arid ecologies with special reference to India; these workers emphasized that agroforestry is the way to life in arid India which plays a key role as a means to harmonize use of scarce resource inputs so as to make production system sustainable and climate smart.

Kemeuze et al. (Chap. 6) have examined land use management by smallholders' households in dry landscapes in the semi-arid area of Cameroon and showed that agroforestry, urban and peri-urban forestry and forest plantations can help to combat desertification and conserve biodiversity and for climate change mitigation and adaptation. Sanogo et al. have reviewed climate change impacts on the delivery of tree ecosystem services in the West African Sahel (Chap. 7), and the presence of trees could enhance the resilience of the local population to climate change through adaptation and mitigation (Chap. 7). In another contribution (Chap. 8), Sileshi et al. explained that trees in agroforestry systems on degraded lands promote closed nutrient cycling; in nutrient-poor soils, there is a need for microbial inoculation of tree seedlings with appropriate N-fixing bacteria and mycorrhizal fungi and application of phosphorus fertilizer for their successful establishment as well as providing these inputs during tree planting in drylands. In Sileshi et al. Chap. 9 have presented synthesis of studies relating to the sustainability of *Gliricidia*-based agroforestry systems for improving soil fertility and as a means to intensify resource-limited agroecosystems. *Gliricidia*-based practices are useful for maximizing resource use, increasing crop production and enriching the soil with organic matter and nutrients. Adopting agroforestry in sub-Saharan Africa within the socio-economic and policy framework has been discussed by Dlamini (Chap. 10) with an emphasis that the agroforestry systems require physical suitability besides enabling conditions, such as governance, gender synergies, secured land tenure, investment and markets for agroforestry inputs and outputs.

The six chapters (Chaps. 11–17) included in Part III (Volume 1) bring together a broad range of examples relating to agroforestry systems and their role in biodiversity conservation in humid and sub-humid regions. Meine van Noordwijk et al. (Chap. 11) have discussed agroforestry options and their constraints for degraded landscapes in Southeast Asia within a drivers–pressures–state–impacts–response framework and lessons learnt across a variety of landscapes representing seven "degradation syndromes," viz. degraded hillslopes, fire-climax grasslands, over-intensified monocropping, forest classification conflicts, drained peatlands, converted mangroves and disturbed soil profiles within a social-ecological system framework. The detailed requirements for effective restoration are highlighted. This contribution clearly shows that all 17 Sustainable Development Goals can contribute to and benefit from a people-centred approach to restoration through agroforestry interventions along with suitable market-based models.

Samsudin et al. have described various traditional agroforestry systems being practised in a degraded peat swamp area and to restore the associate ecosystem in Indonesia and explained community-based peat swamp restoration based on traditional knowledge and agroforestry practices (Chap. 12). Dagar et al. in Chap. 13 stated that afforestation and agroforestry land-use systems are of immense importance for the coastal and island ecologies particularly in the scenario of climate change, with special reference to India; some prominent potential agroforestry systems include plantation-based multi-storeyed integrated cropping systems, homegardens, fodder farming on neglected coconut plantations, aquaculture in combination with forest and fruit trees, alley cropping and mangrove plantations to protect coastlines. In Chap. 14, Nath et al. have analyzed tree diversity, biomass and soil carbon dynamics in slash-and-burn agriculture, ecosystem disservices caused by slash-and-burn agriculture and agroforestry systems suitable for restoring degraded land under slash-and-burn agriculture in north-east India. The authors also have stressed the need for the promotion of tree-based crop production models in slash-and-burn cultivation areas exploring the possibility of implementing appropriate cash-incentive-based mechanism for the adoption of agroforestry systems.

In Chap. 15, Montagnini describes agroforestry systems in tropical Latin America and other regions of the world and shown that multi-strata agroforestry systems of homegardens, successional agroforestry, the silvopastoral systems and living fences and windbreaks in agricultural landscapes have great potential to conserve biodiversity; agroforestry systems can be part of biodiversity islands, especially in buffer zones of protected areas, and payments for environmental services have been successful in Latin America to promote silvopastoral systems, including planting more native trees for conserving biodiversity. On the basis of case studies, Gururaja Rao and Dagar showed that on-farm technologies for *Salvadora persica* and halophytic forage grasses prove to be useful in restoring the coastal saline soils of India and explored the use of halophytes for fodder, fuel, oils, healthcare, eco-restoration, and bioremediation (Chap. 16). Lakshmi and Joseph have analyzed the role of soil biodiversity of microarthropods, the determinants of soil quality of tropical homegardens, as affected by change in soil temperature, soil moisture, soil organic carbon and land management practices (Chap. 17).

In Volume 2, the four chapters (1–4) Section IV, explore the sustainability indicators and soil quality parameters for long-term sustainable production and restoration of temperate agroforestry systems. In Chap. 1, Thevathasan et al. present the long-term studies on tree-based intercropping and riparian buffer agroforestry systems in southern Ontario, Canada, indicating that the maintenance of sustainability indicators (e.g. soil carbon, soil quality, system level carbon sequestration, biodiversity, water quality, nutrient cycling and availability and potential greenhouse gases reduction mechanisms) above a given threshold level contributes to continuous sustainable biomass production. Agroforestry-based biomass production systems can play a major role in sequestering atmospheric CO_2. According to Mugloo et al. (Chap. 2), agroforestry systems have recently been introduced to improve the degraded grasslands as well as to improve fodder availability in north-western Himalayan region of India. Alfaro et al. (Chap. 3) have analyzed the soil quality in deciduous and mixed perennial deciduous old Andean *Nothofagus* forests in south central Chile, indicating possibility of adopting silvopastoral practices for restoring the most degraded sites. Wani et al. have examined trees outside forest (TOF) practices with suitable examples from Jammu and Kashmir in India (Chap. 4).

The twelve chapters (Chaps. 5–16) of Volume 2 included in Part V bring together a broad range of agroforestry interventions for rehabilitation of salt-affected lands, ravine lands and mine spoils and carbon sequestration potential in agroforestry systems. Dagar and Gupta (Chap. 5) have given an overview of the salt-induced land degradation and discussed in detail the agroforestry interventions to rehabilitate salt-affected and waterlogged degraded landscapes with examples from India, South Asia and Australia. They also highlighted soil bio-amelioration, carbon sequestration in plant biomass, soil carbon sequestration and climate change mitigation and adaptation in agroforestry systems on salt lands (Chap. 5). Dagar and Gupta in Chap. 6 have reviewed the status of grazing lands and their production potential, goods and services, the main causes of rangeland degradation and approaches for their management and the potential of silvopasture systems for degraded pasture/grazing lands in different regions of the world. Agri-horticultural agroforestry systems and boundary plantation systems have a great potential for the improvement and utilization of ravine lands for biomass production and carbon sequestration. Optimum utilization of suitable species of trees/shrubs and grasses is important in ravine rehabilitation for the treatment of table and marginal lands as discussed by Parandiyal et al. (Chap. 7). Lal et al. have highlighted urban and peri-urban agroforestry with emphasis on benefits of agroforestry systems by using wastewater for irrigation, suitable trees and crops for wastewater-irrigated agroforestry system, carbon sequestration and ecosystem services, in Chap. 8. Raizada and Dhyani have compiled information of agroforestry rehabilitation of mine spoils in India, indicating that restoration of limestone quarries, iron ore overburden and coal mining areas are successful cases of large-scale post-mining restoration practices in India (Chap. 9). Chaturvedi (Chap. 10) has explained that revegetation through tree plantations on mine spoils is one of the efficient methods of restoring fertility of soil, supporting the establishment of vegetation, enhancing soil fertility and improving carbon sequestration. Ram Newaj et al. (Chap. 11) have explored the potential for carbon sequestration in agroforestry systems, especially on degraded lands, as influenced by the climatic and geographical conditions of the areas in India.

In Chaps. 12 and 13, Sileshi et al. have analysed the sustainability of *Faidherbia albida*-based agroforestry practices in Sub-Saharan Africa using the sustainability intensification framework and case studies in terms of productivity, human well-being, economic and environmental sustainability. They have highlighted that *Faidherbia*-based agroforestry is important towards increasing productivity and environmental sustainability, especially, in the nutrient-poor arid and semi-arid ecosystems.

In Chap. 13, Moussa et al. have reported that Agroforestry parklands are the predominant agro-ecosystems in West Africa, the key tree components being *Prosopis africana* and *Faidherbia albida*; and modern dendrochronology methods can be used to analyse the responses of trees to climate variability in agroforestry parklands in the drylands of south-central Niger. In Chap. 14, Jaiswal et al. have analysed opportunities for farm and tribal communities for transforming the traditional lac-based agroforestry into modern remunerative venture for degraded lands, particularly, in the Indian context. In degraded lands of semi-arid regions in Africa, Dzerefos et al. (Chap. 15) have emphasized monitoring of host plants that provide insect shelter, water and food, adaptive management of the agro-ecosystem, and ensuring persistence of beneficial insects. Solomon et al. in Chap. 16 have compiled existing information on social, economic, and ecological implications of bamboo-based agroforestry with suitable examples from Asian and African regions, and their role in enhancing ecosystem services.

Research developments in agroforestry in different degraded landscapes in tropical, subtropical and temperate regions, on the basis of research work discussed by the contributors in Volume 1 and Volume 2 of this book, have been synthesized in the concluding chapter by Dagar and Gupta (Chap. 17).

1.7 Conclusions

Agroforestry systems are vital for healthy and productive landscapes and are the key to the pressing challenges of land degradation and for climate mitigation and adaptation, biodiversity conservation and livelihood security. Successful restoration of degraded lands can happen through agroforestry interventions by taking practical steps to integrate a greater number and variety of tree species into farms, fields and forests and allowing natural regeneration of degraded landscapes. Agroforestry research now has provided useful technological and policy innovations that are rapidly spreading in Africa, Asia, Latin America and more recently in several developed countries. Now, agroforestry is considered not only for sustainable production system but also a problem-solving science. For example, agroforestry systems are playing a vital role for rehabilitation of degraded lands, mitigating climate change through carbon sequestration, employment generation and food and nutrient security. We have gone a long way to develop several agroforestry models for reclaiming salty and waterlogged soils, rehabilitation of ravine lands, restoration of mine spoil areas, restoration of degraded mangrove areas, domestication of indigenous fruit trees and urban and peri-urban agroforestry. The silvopastoral systems have potential to restore the most degraded sites through improvement of the soil quality.

Research and development efforts in the future should strive to focus on bringing agroforestry for utilizing degraded lands at various spatial levels ranging from farm to ecosystem and landscape for the benefit of the landowners and farmers. To maximize productivity in agroforestry systems, sequester more carbon in soil or understand how degraded landscapes will further shift in response to human activities, there is urgent need for greater understanding of the role of biodiversity in ecosystem functioning and soil carbon sequestration. Despite the obvious benefits, agroforestry continues to face challenges, such as unfavourable policy environment, lack of scientific knowledge and public awareness, legal constraints and poor coordination and convergence among the multiple sectors involved, namely, agriculture, forestry, rural development, environment and trade. Inadequate investment, lack of suitable extension strategies and weak market linkages are the real challenges for agroforestry development. Moreover, the development of agroforestry is impeded by legal, policy and institutional arrangements; its environmental benefits are mostly unrewarded; and the investments are mostly linked with long gestation periods. As a result, the potential of agroforestry has not been fully understood by the farming communities and also policymakers.

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2 Agroforestry for Rehabilitation of Degraded Landscapes: Achieving Livelihood and Environmental Security

Sharda Rani Gupta, Jagdish Chander Dagar, and Demel Teketay

Abstract

Land degradation is occurring in almost all terrestrial biomes and agroecologies, in both low- and high-income countries. However, its impact is especially severe on the livelihoods of the poor, who are heavily dependent on natural resources. About two billion ha of land in the world is affected by various forms of natural and human-induced land degradation, water erosion being the main contributor (1.1 billion ha). Several scientific reports highlighted in this review show the extent to which soil degradation is threatening food security as well as ecosystem goods and services and depleting ecosystems in different regions of the world. Ecological restoration of degraded ecosystems is a global priority. The various restoration projects range in size from plot to regional level using site-specific abiotic and biotic interventions. Agroforestry encompasses a wide range of approaches and technologies for restoring degraded lands. Agroforestry options are being used to rehabilitate/restore degraded lands from intensive agriculture, soil erosion, deforestation, rangeland degradation, mining and overextraction at various scales, from plot, to ecosystem, to landscape level. By applying appropriate agroforestry technologies, involving various species of forest and fruit trees, forages, arable crops, high-value medicinal crops, dairy and meat livestock, fish and poultry, the production systems can be successfully more remunerative.

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Agroforestry systems (AFS), which are increasingly being considered as climate-smart agriculture, have been designed for optimization of desired outputs, such as timber or fuelwood (agrisilviculture), or for specific land rehabilitation objectives, such as protection of soil from erosion (alley cropping and sand dune stabilization), reclamation of salt lands (silvopastoral systems involving salt-adapted trees, grasses and halophytes), checking waterlogging/seepage (strip plantation along canals or boundary plantations), utilization of waste/sewage water (urban or peri-urban forestry) and assuring livelihood and nutritional security of small and marginal farmers (homegardens and social forestry). AFS play an effective role in improving soil fertility, conserving biodiversity, enhancing carbon sequestration and providing climate change mitigation and adaptation. However, there is a need to involve different stakeholders to design effective AFS for supporting sustainable productivity of land and enhancing biodiversity and ecosystem services at plot and landscape scales, to identify best practices to diversify AFS and better understand soil properties and land use in degraded landscapes.

Keywords

Land degradation · Landscape restoration · Agroforestry systems · Environmental services · Biodiversity conservation · Carbon sequestration · Soil fertility · Climate change mitigation and adaptation

2.1 Introduction

Sustainable land use and protection of soils play a key role in food, climate and human security (Lal 2014; Amundson et al. 2015). In spite of this, land degradation has become a global phenomenon as influenced by natural and socio-economic factors; it is occurring in most terrestrial biomes and agroecologies, in both low-income and highly industrialized countries (Nkonya and Mirzabaev 2016). On the other hand, fertile soils are a non-renewable resource on human life spans as their formation and renewal could take hundreds, if not thousands, of years (Lal 1994). For this reason, the human management of soil resources will have wide-ranging consequences for food and environmental security as 99% of the world's food comes from the terrestrial ecosystems.

Land degradation is the long-term loss of production capacity of land and ecosystem services, affecting the livelihoods and food security of billions of people (MEA 2005a). Land degradation results in decreased food production, poor water storage, biodiversity loss, loss of soil organic carbon and loss of ecosystem services (IUCN et al. 2015; Gilbey et al. 2019). The main causes of land degradation are inappropriate land use and management, loss of soil organic carbon, soil erosion, salinization, acidification, waterlogging, desertification, mining, soil compaction, loss of soil biodiversity, nutrient imbalance and loss of soil biodiversity (FAO and ITPS 2015). Recently, the International Platform for Biodiversity and Ecosystem Services reported that more than 75% of Earth's land areas are substantially degraded and are adversely impacting the well-being of at least 3.2 billion people globally (IPBES 2018). The annual cost of land degradation has been estimated at 10% of global gross domestic production in terms of loss of biodiversity and ecosystem services (IPBES 2018). Rapid expansion and unsustainable management of croplands and grazing lands are the most extensive direct drivers of land degradation, causing significant loss of biodiversity and ecosystem services. Avoiding, reducing or reversing land degradation is essential for achieving the majority of the Sustainable Development Goals (SDGs) by 2030. Agroforestry has an important role in providing food and nutritional security (Pretty and Bharucha 2014; Dagar and Tewari 2017; Waldron et al. 2017; Elevitch et al. 2018), controlling land degradation (Lal 2004; Nair 2007; Dagar and Singh 2018) and supporting environmental benefits across a range of landscapes and economies (Jose et al. 2012; Hillbrand et al. 2017; Udawatta et al. 2017; Gupta et al. 2019).

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; it aims to balance diverse types of tree cover to achieve multiple benefits, based on the local socioecological conditions and stakeholder engagement (Mansourian and Parrotta 2018). FLR is a mechanism to achieve multiple goals, including climate mitigation, biodiversity conservation, socio-economic benefits, food security and ecosystem services (IUCN and WRI 2014; Hanson et al. 2015; Chazdon and Brancalion 2019). The forest landscape approach is vital to reaching the global scales so as to reverse the effects of deforestation and land degradation (Chazdon and Brancalion 2019). Agroforestry FLR encompasses all activities that combine trees with an agricultural landscape composed 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.

Agroforestry as a tool for forest and landscape restoration can improve soil fertility, enhance nutrient cycling, control soil erosion and regulate soil water availability. Agroforestry acts as an effective means of improving soil productivity (Kaur et al. 2002a, b; Acharya and Kafle 2009; Rodrigues et al. 2015; Salim et al. 2018; Udawatta et al. 2017), controlling soil salinity and waterlogging (Dagar et al. 2016a, b; Dagar and Minhas 2016), enhancing erosion control (see Reij and Garrity 2016; Dagar and Singh 2018), increasing water availability (Siriri et al. 2012), improving biodiversity (Nair and Garrity 2012; Dagar et al. 2019) and mitigating climate change through environment improvement and carbon sequestration (Zomer et al. 2016; Dagar and Tewari 2016, 2017; Feliciano et al. 2018; Shi et al. 2018; Dagar et al. 2019; Gupta et al. 2019). Agroforestry can add a high level of diversity on degraded lands for supporting numerous ecological and production services (Schoeneberger et al. 2012; Singh et al. 2016; Peri et al. 2017; Dagar et al. 2016a, b; Gupta et al. 2019) as well as providing resilience to climate change impacts. 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 and increased soil fertility and environmental services (Jose et al. 2012; Dagar and Tewari 2017; Agroforestry Network and Vi-skogen 2018).

This chapter is to discuss the global extent of land degradation, ecological restoration of degraded landscapes, agroforestry systems suitable for degraded landscapes and the potential of agroforestry systems to provide various environmental services contributing to biodiversity conservation, livelihood security and mitigating climate change.

2.2 Global Context of Land Degradation

"Land degradation is a long-term loss of ecosystem functions and services, caused by disturbances from which the system cannot recover unaided" (Dent 2007). 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). The IUCN report has analyzed the drivers and pressures of land degradation as illustrated in Fig. 2.1. According to Geist and Lambin (2004), *proximate causes of land degradation* are human activities or immediate actions at the local level, such as cropland expansion, that originate from intended land use. The fundamental social and biophysical processes, such as human population dynamics or agricultural policies, constitute the *underlying driving forces*, underpinning the proximate causes which operate at the local level

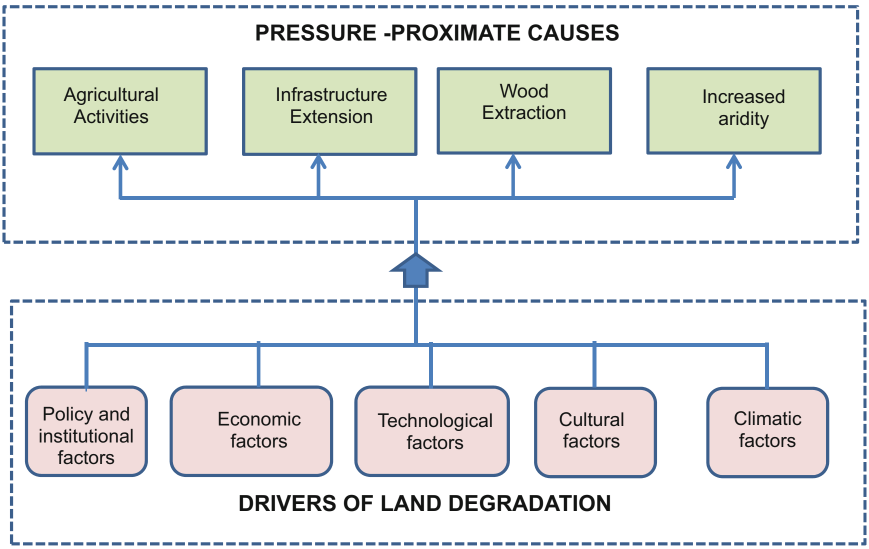

Fig. 2.1 Proximate and underlying driving forces of land degradation (adapted from Gichuki et al. (2019) based on IUCN et al. (2015) and Geist and Lambin 2004)

or reflect influences at the national or global level (Geist and Lambin 2004). The expansion of agriculture and grazing lands into native vegetation, unsustainable agricultural and forestry practices, global consumption patterns and climate change are the main drivers of land degradation (Sutton et al. 2016; UNCCD 2017). Other contributory factors to degradation include urbanization, infrastructure development and landscape modifications through extractive industries (UNCCD 2017). Land degradation results in a decrease in the provision of terrestrial ecosystem services, having direct economic costs, such as increased food prices as well as far-reaching socio-economic consequences, in terms of food and water insecurity and malnutrition. Further increase in land degradation can slow down plans to alleviate poverty and hunger, ensure food security and build resilience to drought and water stress (Gichuki et al. 2019). There could be conflicts over scarce resources leading to forced migration. There is urgent need to protect, restore and manage land and soils sustainably to overcome the many challenges countries face as well as to achieve global climate and biodiversity commitments (Gichuki et al. 2019).

Since the first global mapping of desertification in 1977 (Dregne 1977), there have been numerous efforts on global mapping of land degradation (Oldeman et al. 1990; USDA-NRCS 1998; Eswaran et al. 2001; Hill et al. 2008; Bai et al. 2013). The earlier studies had been constrained by lack of global-level quantitative data, which could be used for mapping soil and land degradation, and, therefore, were based on expert opinions. The developments in the field of remote sensing and satellite technologies allowed the recent studies to be based on quantitative satellite data, such as Global Inventory Modelling and Mapping Studies (GIMMS) dataset of 64 km^2 resolution of normalized difference vegetation index (NDVI) data. However, several methodological challenges still exist on estimating the land degradation hotspots more accurately (Le et al. 2012, 2016).

Gibbs and Salmon (2015), while reviewing prominent databases and methodologies for estimating the area of degraded lands, discussed four approaches used to assess degraded lands at the global scale. These include expert opinion, satellite observations, biophysical models and taking inventories of abandoned agricultural lands. Each of these approaches, which use maps and quantify the degraded lands, has several benefits and limitations. The FAO's Global Assessment of Land Degradation and Improvement (GLADA) project has quantified land degradation by using the normalized difference vegetation index (NDVI), which is widely used to assess vegetation condition and productivity (Bai et al. 2008a). The early results reveal a declining trend in net primary productivity across 21% of the global land area (2.74 billion ha), mainly in tropical Africa (south of the equator), Southeast Asia, South China, north-central Australia, drylands and sloping-lands of Central America and the Caribbean, Southern Brazil, the Pampas and swaths of the boreal forest in Siberia and North America (Bai et al. 2008b), and nearly one-fifth of this degraded land (20% of all cultivated area) is cropland (Bai et al. 2008a; FAO 2013). Global estimates of total degraded area vary from less than one billion ha to over six billion ha (Table 2.1), with equally wide disagreement in their spatial distribution (Gibbs and Salmon 2015).

The recent estimates show that 25% of the world's lands are either highly degraded or subject to high rates of degradation (FAO 2011; FAO and ITPS

Table 2.1 Continental and global estimates (million ha) of land degradation [compiled by Gibbs and Salmon (2015); modified by Dagar and Gupta (2016)]

Area	GLASOD	FAO TerraSTAT	GLADA (Bai et al. 2008a, b)	Campbell et al. (2008)	Cai et al. (2011)
Africa	321	1222	660	69	132
Asia	453	2501	912	118	490
Australia and Pacific	6	368	236	74	13
Europe	158	493	65	60	104
North America	140	796	469	79	96
South America	139	851	398	69	156
World (Total)	1216	6140	2740	470	991

2015). These degraded lands are those that have been converted into deserts or polluted or deforested and converted to agriculture. 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.

Using the long-term trend of biomass productivity as a proxy of land degradation at the global scale, Le et al. (2016) have identified the degradation hotspots in the world across major land cover types. They corrected factors confounding the relationship between the remotely sensed vegetation index and land-based biomass productivity, including the effects of interannual rainfall variation, atmospheric fertilization and intensive use of chemical fertilizers. Their findings show that land degradation hotspots cover about 29% of global land area and are happening in all agroecologies and land cover types. One-third of this degradation is directly identifiable from a statistically significant declining trend in NDVI. However, the remaining two-thirds of this degradation are concealed by rainfall dynamics, atmospheric fertilization and application of chemical fertilizers. Globally, areas affected by human-induced biomass productivity decline are found in 25% of croplands and vegetation-crop mosaics, 29% of mosaics of forests with shrub lands and grasslands, 25% of shrub lands, and 33% of grasslands, as well as 23% of areas with sparse vegetation. About 3.2 billion people reside in these degrading areas (Le et al. 2016). However, the number of people affected by land degradation is likely to be higher as more people depend on the continuous flow of ecosystem goods and services from these affected areas.

The FAO and ITPS (2015) have identified 13 forms of soil degradation, causing land degradation. Land degradation from erosion of conventional agricultural systems is three times greater than that in conservation agriculture and over 75 times greater than erosion under native vegetation (Montgomery 2007). It is estimated globally that soil erosion caused by water is 20–30 Gt year^{-1}, and erosion caused by tillage may amount to ~5 Gt year^{-1} (FAO and ITPS 2015). Total rates for wind erosion are highly uncertain. According to Li and Fang (2016), erosion rates

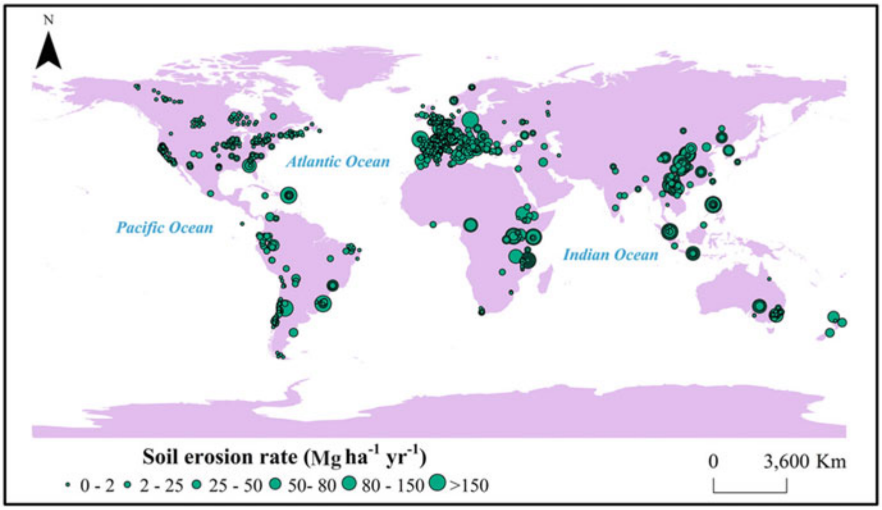

Fig. 2.2 Global soil erosion rates in Mg ha^{-1} year^{-1} (based on database from García-Ruiz et al. 2015). Source: Li and Fang (2016), reprinted with kind copyright permission from Earth-Science Reviews. © 2016 Elsevier

vary in different parts of the world due to different climates, topographic conditions, soil types, and land covers (Fig. 2.2) and most of the average erosion rates in cultivated lands in different regions are in excess of 1 Mg ha^{-1} year^{-1}. The US comprised the largest number of data, followed by Spain and China; the Middle East, South America and western Africa had little available information (García-Ruiz et al. 2015). The overall severity and the spatial distribution of soil erosion around the world is reflected in Fig. 2.2.

Soil erosion is broadly defined as the accelerated removal of topsoil from the land surface through water, wind or tillage. Water erosion is the major type of erosion in the regions of South and East Asia with alternating dry and wet seasons, whereas wind is the key driving force inducing soil erosion in the drier and desert areas. Serious 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 is concentrated mainly in the most western and northern arid and semi-arid regions of Afghanistan, Pakistan, India and China. There is substantial area of acid soils distributed in tropical and subtropical regions of Asia, mainly in Southeast Asia as well as parts of East and South Asia. In the semi-arid and arid zones of Central and West Asia, salt-affected soils are widely distributed (Toderich et al. 2013). On the other hand, salt-affected soils are prevalent in certain coastal areas in monsoon zones in South and Southeast Asia because of intrusion of salty water.

In Latin America and the Caribbean, water erosion and landslides are prominent threats in the sloping lands of the mountains, especially when the slopes have been burned and overgrazed (FAO and ITPS 2015). Loss of soil carbon, mostly, occurs after deforestation and intensive cultivation of grasslands and monoculture. In semi-arid and arid areas, salinity and sodicity are important threats to soil; nearly one billion ha of land is impacted by salinity representing about 7% of land area globally (Wicke et al. 2011).

Drylands occur in all parts of the world and cover an area of 6.1 billion ha of the Earth's land surface (FAO 2016) and are sensitive to degradation (Reynolds et al. 2007). The principal processes of land degradation include erosion by water and wind, chemical degradation (comprising acidification, salinization, fertility depletion, and decrease in cation retention capacity), physical degradation (comprising crusting, compaction, hard-setting, etc.) and biological degradation (reduction in total and biomass carbon and decline in land biodiversity) (Sivakumar 2007). At the landscape scale, the degradation leads to a loss of biodiversity and causes negative microclimatic changes leading to desertification. About 40% of lands in the African continent (65% of arable land, 30% of grazing land and 20% of forests) are under serious degradation, especially due to soil erosion, soil nutrient depletion, soil organic matter decline and soil biodiversity loss (FAO and ITPS 2015). In sub-Saharan Africa (SSA), the agriculture and livestock yields are lowest than any region in the world due to land degradation, mainly due to desertification (FAO and ITPS 2015).

Ecosystem degradation, for example, includes the loss of soil or soil health in croplands, deforestation, habitat fragmentation, expansion of agriculture, conversion to industrial plantations, fire in forests (FAO 2015; Hansen et al. 2013; Song et al. 2018), overgrazing, unsustainable fuelwood use and woody plant expansion in rangelands (Asner et al. 2004; Angerer et al. 2015; Reeves and Baggett 2014) and drainage and eutrophication in wetlands. There are a number of assessments that focus on biodiversity loss to estimate the degree and extent of ecosystem degradation. The Living Planet Index (LPI) is one of the longest-running measures to assess the trends in the state of global biodiversity and health of our planet (WWF 2010). By using trends in the size of 16,704 populations of 4005 mammal, bird, reptile, amphibian and fish species from different biomes and regions, a 60% global decline has been shown in LPI between 1970 and 2014 (WWF 2018).

Since 2000, about 13 million ha of forest have been lost each year. Between 1990 and 2015, the world's forests decreased from 31.6% of the land area to 30.6% (FAO 2015). This loss occurred, mainly, in sub-Saharan Africa, Latin America and Southeast Asia. In the Amazon, industrial-scale cattle ranching and soybean production for world markets are increasingly important causes of deforestation. In Indonesia, the conversion of tropical forest to commercial palm tree plantations to produce biofuels for export is a major cause of deforestation in Borneo and Sumatra.

Expansion of agriculture is, indeed, the primary driver of deforestation in the tropics (Hansen et al. 2013). Clearing of natural vegetation for export-oriented industrial agriculture has also been observed over large areas in the Cerrado and the Gran Chaco in Latin America (Song et al. 2018). In SSA, tree cover loss was pervasive across the Congolian rainforests and the miombo woodlands (Song et al. 2018), historically related to smallholder agriculture and, increasingly, commodity crop cultivation (Ordway et al. 2017).

Using satellite imagery, Curtis et al. (2018) developed a forest loss classification model to analyze a spatial attribution of forest disturbance to the dominant drivers of

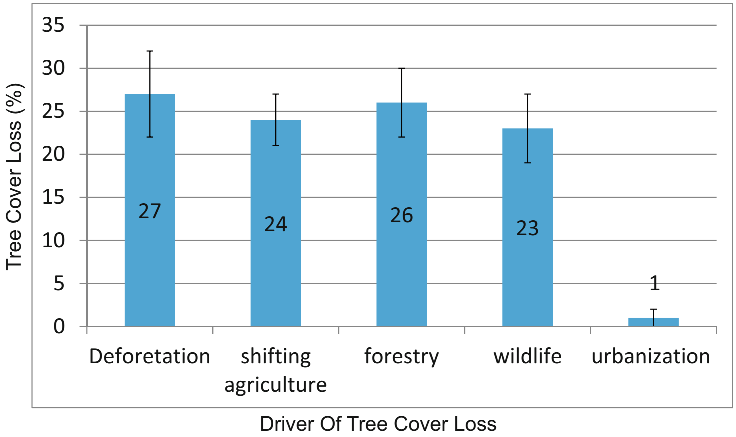

Fig. 2.3 The drivers of tree cover loss: 2001–2015 globally [based on Curtis et al. (2018)]

land cover and land use change over the period 2001 to 2015. Overall, the study showed that 27% of all forest loss is caused by permanent commodity-driven deforestation to grow commodity crops (Fig. 2.3). The major drivers of forest loss worldwide are forestry plantations (26%), wildfire (23%) and shifting agriculture (24%) (Curtis et al. 2018). Only a very small area of forest loss (less than 1%) could be attributed to urbanization. The study indicated that commodity-driven deforestation is concentrated primarily in Latin America and Southeast Asia. In Latin America, row cropping and cattle grazing were found to be the primary drivers of forest loss, while oil palm cultivation is the main cause of forest loss in Malaysia and Indonesia.

2.3 Restoration at the Ecosystem and Landscape Level

Restoration is the process of improving ecosystem structure and functions of degraded lands. The relevant definition of restoration is "the act of restoring to a former state or position or to an impaired or perfect condition" (Bradshaw 1997). The activities necessary to bring a disturbed site into former or original state involve manipulation of nature to recreate species composition and ecosystem processes close to the state that existed before disturbance (Singh et al. 2014a, b). It re-establishes the structure, productivity and species diversity of the original community (Fig. 2.3). 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. The relevant definition of restoration (SER 2004) is "the act of restoring to a former state or position or to an impaired or perfect condition." The interventions required to bring a disturbed ecosystem into original state involve manipulation of nature to recreate species composition and ecosystem processes close to the state that existed before disturbance (SER 2004; Singh et al. 2014a, b). During restoration, the structure, productivity and species diversity of the original community is re-established. However, the degraded

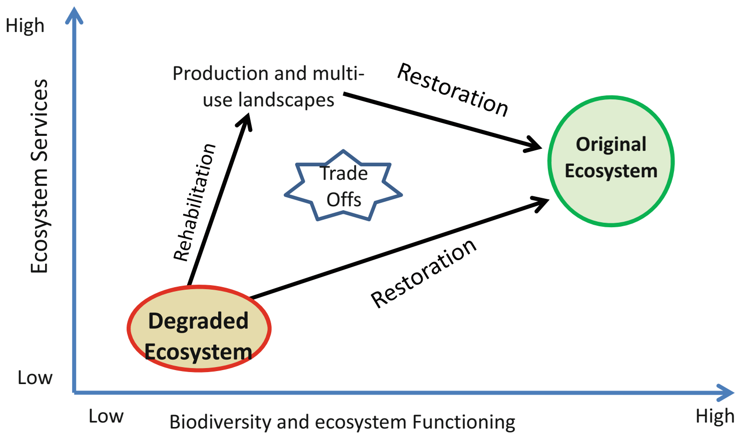

Fig. 2.4 Conceptual framework for ecosystem degradation, rehabilitation and restoration (modified from Bradshaw 1997). It shows various types of managed and unmanaged systems along the *x*–*y* axes: increasing biodiversity and ecosystem functioning (*x*-axis) and increasing ecosystem services (*y*-axis). The arrows indicate possible interventions for transitioning from one system to another (adapted from UNEP/CBD/COP/12/INF/18)

ecosystem exhibits a lower level of structure and function, compared with that of the original ecosystem.

Rehabilitation activities aim to repair ecosystem functioning with less emphasis on the recovery of structure and composition and more on increasing productivity for the benefit of people (Clewell and Aronson 2013). Thus, rehabilitation efforts are more relevant to production and multi-use landscapes with many proven approaches and technologies to progress from a less desired to a more desired ecosystem state (Fig. 2.4).

A radar diagram can be used to illustrate change in the status of ecosystem services associated with restoration and rehabilitation (Fig. 2.5) which help to minimize trade-offs between desired socio-economic benefits and the associated but undesired decline in biodiversity, soil health and water quality (Fig. 2.5). In addition to the four categories of ecosystem services, i.e. provisioning, regulating, cultural and supporting services (MEA 2005b), "habitat services" (de Groot 1992) have been added to highlight those services with no direct or indirect benefit to humans. Even if the focus of rehabilitation is on maximizing the production function, e.g. provisioning services, most often, the measures taken will positively contribute to the improvement of essential supporting and regulating services. The terms remediation, revegetation and reclamation are often seen as the first steps or actions to be taken in rehabilitation or restoration projects and programmes, particularly in severely degraded or contaminated ecosystems (Singh et al. 2014a, b).

In different regions of the world, efforts are underway in both terrestrial and aquatic ecosystems for restoring biodiversity, ecosystem services and mitigating the risks of global change (McCarty and Zedler 2002). The IUCN Commission on Ecosystem Management has adopted ecosystem approach for promoting ecosystem

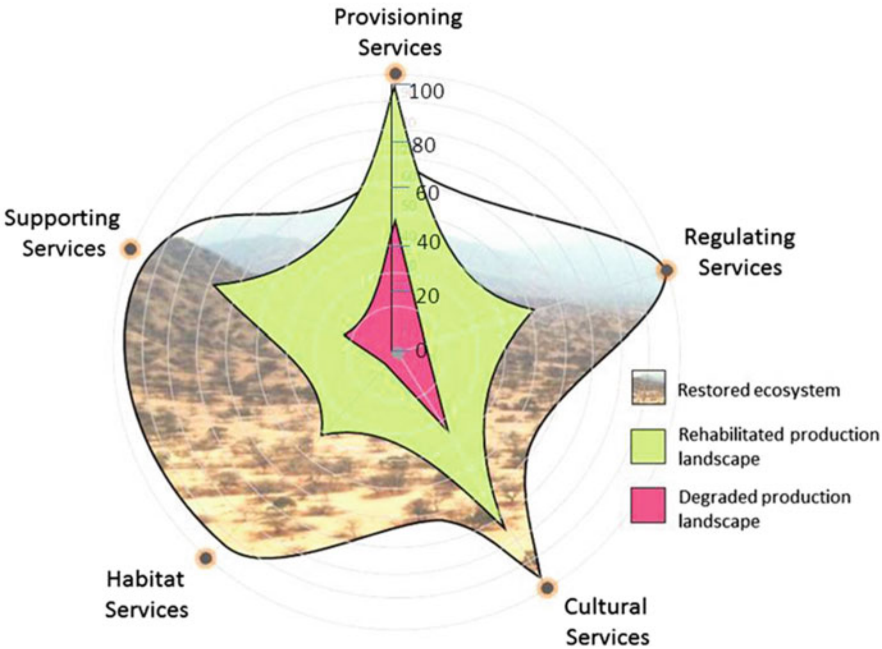

Fig. 2.5 The radar diagram illustrates change in the status of the five major types of ecosystem services provided by degraded production landscapes, rehabilitated production landscapes, and restored ecosystems (adapted from Alexander et al. 2016; Ecology and Society 21(1):34. https://doi.org/10.5751/ES-08288-210134)

restoration for sustainable development. According to Hobbs and Cramer (2008), the various restoration projects in different regions of the world range in size from local to regional scales using site-specific abiotic and biotic interventions leading to enhanced environmental goods and services and improved human well-being. Most of the forest restoration programmes have been conducted on project scales by using non-cost-effective approaches without much consideration to gaining multiple benefits and long-term sustainable outcomes (Holl 2017).

Many countries, including Costa Rica, Niger, South Korea, China, India and Ethiopia, have achieved success through forest landscape restoration (www.wri.org/restorationdiagnostic, accessed on 11-06-2019). 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 areas, biodiversity improved substantially (WRI 2008). In India, watershed restoration efforts since the 1970s have addressed soil and water conservation needs across 45 million ha of arable and nonarable lands (Chaturvedi et al. 2014). The HASHI programme was implemented since the 1980s in the Shinyanga Region in Tanzania in response to ecosystem degradation problems; the programme used a multisectoral approach for woodland reclamation, pasture management, soil conservation and water resource management (Duguma et al. 2015).

Forest landscape restoration is the process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes (Maginnis et al. 2005). Forest landscape restoration (FLR) includes a wide range of activities that have been categorized in the Restoration Opportunities Assessment Methodology (ROAM) (IUCN and WRI 2014). For example, a variety of restoration interventions or technological options, such as supporting community-managed forests or encouraging agroforestry systems in degraded forest land and permanently agricultural managed lands, protective lands or buffers and farmer-managed natural regeneration, are being used in FLR (IUCN and WRI 2014).

Restoring forests and forest landscapes is an important step in regaining the health and functionality of these ecosystems. Forest landscape restoration is an integrated approach that takes into consideration all aspects of forest landscapes and their management (Baig et al. 2017). The landscape approach considers restoration as a mosaic of land uses, including agriculture, farming and pastoral systems. For example, agroforestry and silvopastoral approaches are effective means through which forest landscape restoration can enhance adaptive capacity and resilience by increasing species diversity and variation within a landscape (Baig et al. 2017). Bastin et al. (2019) have clearly emphasized the urgency of planting and sustaining restoration systems globally, while Chazdon and Brancalion (2019) stressed the need for developing appropriate mechanisms for restoration by mobilizing resources in cost-effective ways.

Restoration of ecosystems is recognized by existing international conventions and agreements as a key undertaking to achieve their goals, including the SDGs, Strategic Plan for Biodiversity 2020 and its Aichi Biodiversity Targets, UN Framework Convention on Climate Change (UNFCCC) and Paris Agreement, UN Convention to Combat Desertification (UNCCD) and Land Degradation Neutrality Target Setting, Ramsar Convention and UN Strategic Plan for Forests 2017–2030. The UN Decade on Ecosystem Restoration in 2019 has the main focus on landscapes of interacting land uses where ecological, social and developmental priorities can be balanced. Ecosystem restoration, through a landscape approach, involves adaptive management, ensuring the resilience of the landscape in the long term.

2.4 The Global Scenario of Agroforestry

Historically, agroforestry is an age-old land-use system since time immemorial as the process of human evolution has been from forests when early humans learnt the art of cultivating plants and domesticating animals. The hunting and food-gathering system gradually gave way to food production systems. There are innumerable examples of traditional land-use practices involving combined cultivation of trees and agricultural species on the same piece of land in many parts of the world (Garrity

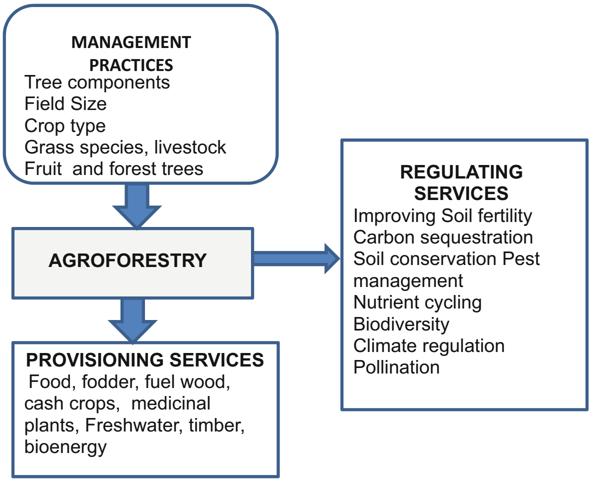

Fig. 2.6 The environmental services of agroforestry systems in degraded landscapes

et al. 2010; Nair 1993). Trees were an integral part of these farming systems, and they were deliberately retained on farmlands to support agriculture. Although agroforestry systems have been traditionally practised in many different forms across the world, they only attracted the attention of the workers in the 1970s–1980s, when greater attention was placed on finding alternatives to increase agricultural productivity, improve degraded lands and improve human well-being of small landholders, especially in the more impoverished tropical regions of the world.

The systematic research in agroforestry gained momentum with the establishment of the International Council for Research in Agroforestry (ICRAF, now the World Agroforestry Centre) in 1978 in Nairobi, Kenya. The World Agroforestry Centre now defines agroforestry as "a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels" (www.icraf.cgiar.org, accessed on 31-05-2019). Agroforestry systems, particularly in degraded landscapes, not only have enormous benefits in the provision of food for local people but also provide multiple environmental services and influence the sociocultural values (Fig. 2.6). They play an important role in reducing biodiversity loss, as these systems provide habitat for a richer variety of species than agricultural systems with annual crops (Jose 2012).

Agricultural land with more than 10% tree cover is considered as agroforestry land, and to estimate the extent of agroforestry, the adopted techniques include remote sensing, satellite or other aerial photography (Zomer et al. 2014). By the year 2010, more than 43% of all agricultural land in the world was under some kind of agroforestry and an estimated 1.2 billion people around the world dependent upon agroforestry systems (Zomer et al. 2016). Agroforestry is, especially, widespread in Asia, Central America and South America. In sub-Saharan Africa, the proportion of agroforestry has been estimated at 29% of the agricultural land, accommodating 70 million people (The World Bank 2004).

Millions of ha of land around the world are now covered with agroforestry systems, including 2.8 million ha of rubber forest in Indonesia, 7.8 million ha of cocoa agroforestry worldwide, 9.2 million ha of silvopastoral systems in Central America and 5.1 million ha (90% of country's agricultural land) of diverse agroforestry systems (IIASTD 2009). A variety of agroforestry practices are used around the world (see Nair 1993, Nair et al. 2010; Dagar et al. 2014a, b; Dagar and Tewari 2017; Bhardwaj et al. 2017; Lovell et al. 2017; Chará et al. 2018; Jose and Dollinger 2019). Many of the anecdotal agroforestry practices, which are time tested and evolved through traditional indigenous knowledge, are still being followed in different agroecological zones. The traditional knowledge and the underlying ecological principles concerning indigenous agroforestry systems around the world have been successfully used in designing the improved systems. Many of them, such as improved fallows, homegardens and parkland systems, have evolved as modern agroforestry systems. Climate-smart agriculture (CSA), involving agroforestry component, is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate. CSA aims to tackle three main objectives: (1) sustainably increasing agricultural productivity and incomes, (2) adapting and building resilience to climate change and (3) reducing and/or removing greenhouse gas emissions, where possible (http://www.fao.org/climate-smart-agriculture/en/, accessed on 31-05-2019). These objectives can successfully be met by only adopting agroforestry-based practices.

The forms of agroforestry systems vary considerably from landscape to landscape, country to country and region to region, depending on the prevailing environmental and socio-economic conditions as well as human needs. According to Nair et al. (2010), the major agroforestry practices in tropical and subtropical regions are alley cropping (hedgerow intercropping), homegardens, improved fallow, multipurpose trees on farms and rangelands, silvopasture, shaded perennial crop systems, shelterbelts and windbreaks and Taungya. Silvopasture represents an integrated land-use practice that combines trees, forage and livestock and has been in existence for millennia (see Jose and Dollinger 2019). In Southeast Asia, farmers have practised agroforestry for a long time, and the various types of agroforestry systems on the basis of their mode of origin are categorized as traditional homegardens, improved fallows, "Taungya," hedgerow planting/alley cropping, multistorey system/forest garden and rice terraces with forest agroforestry system (Catacutan et al. 2017). 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. Several workers have described many indigenous and modern agroforestry systems of coastal and island regions of India (Dagar et al. 2014a, b; Velmurugan et al. 2015, 2016; Dagar and Minhas 2016).

As discussed later in this book, some of the common agroforestry practices found in different regions of Africa include shifting cultivation, Taungya and Shamba systems, rotational woodlot system, improved tree fallows, homegardens, parkland systems and silvopastoral systems. The distribution of agroforestry systems in different ecological and geographical regions reveals that there is a close relationship between the ecological characteristics of a region and the nature of the agroforestry systems of that region (Dagar and Tewari 2017; Dagar and Singh 2018).

In North America and other temperate zones, riparian buffers, alley cropping, windbreaks, silvopasture and forest farming are the major agroforestry practices (Nair et al. 2010; Udawatta et al. 2017; Thevathasan et al. 2012). The scope of temperate agroforestry is expanding and has attracted the attention of several research workers (see Lovell et al. 2017). The study sites across the Midwest United States and Southern France represent examples of replicable agroforestry research on a larger scale in temperate regions (Lovell et al. 2017; Udawatta et al. 2017). Across the Canadian prairies, the common agroforestry systems include shelterbelts, hedgerows and silvopasture (Kort and Turnock 1999; Kort et al. 2014), while alley cropping is common in Eastern Canada (Thevathasan and Gordon 1997; Oelbermann et al. 2004; Oelbermann et al. 2006; Thevathasan et al. 2012).

2.5 Agroforestry Systems Suitable for Degraded Lands

Agroforestry is mainly practised on degraded landscapes, which otherwise remain unutilized and, therefore, play a very vital role, particularly in developing countries. Agroforestry encompasses a wide range of approaches and technologies for restoring degraded lands, thereby contributing to landscape restoration.

Some agroforestry systems suitable for rehabilitating or restoring degraded landscapes affected by soil erosion, salinization, physical degradation, loss of nutrients and/or soil organic matter (SOM), waterlogging and mining are briefly discussed in the following sections.

2.5.1 Agroforestry for Reduced Soil Erosion

In India, the sloping lands are planted with alley crops, such as *Gliricidia sepium*, *Leucaena leucocephala*, *Cassia siamea*, *Morus alba*, *Pithecellobium dulce* and *Cajanus cajan*, and fodder grasses as intercrops (Dagar 1995; Dagar et al. 2014a, b). Sajjapongse et al. (2002) developed a sustainable alley cropping model on sloping lands in China by planting day lily (*Hemerocallis* sp.), pears (*Pyrus* spp.) and Chinese prickly ash (*Zanthoxylum* spp.) as hedgerow crops and corn and soybean and sweet potato as alley crops in interspaces, whereas K application was emphasized in the balanced fertilizer treatments. They obtained 115% higher corn yield as compared to farmers' practice, and soil loss was greatly reduced by alley cropping, ranging from 60 to 80%. In North China, *Ziziphus jujuba* is intercropped with agricultural crops (Yin et al. 2008) and is an important pattern of agroforestry, which is distributed widely (Chang et al. 2017; Qiao et al. 2019). Agroforestry is the most effective way to restore the degraded lands on the Loess Plateau and to develop the poor local economy (Peng et al. 2009; Gao et al. 2013).

Soil erosion due to deforestation and high rainfall is a serious problem in many parts of Southeast Asia, particularly in the hilly and mountainous landscapes. For most of the uplands in Southeast Asia susceptible to soil erosion, agroforestry practices, based on contour hedgerow intercropping, have been advocated as biological means to control soil erosion (Catacutan et al. 2017). In these systems, hedgerows of leguminous tree or shrub species are planted in single or double rows along contour lines of sloping fields. In Indonesia, *Gliricidia sepium*, *Flemingia congesta*, *Erythrina* spp., *Senna spectabilis*, and *Calliandra calothyrsus* are planted in hedgerows, whereas annual crops are planted between hedgerows. In the Philippines, Sloping Agricultural Land Technologies (SALT) is a diversified farming system, which can be considered as agroforestry since rows of permanent shrubs like coffee, cacao, citrus and other fruit trees are dispersed throughout the farm plot; the strips, not occupied by permanent crops, however, are planted alternately to cereals (e.g. corn, upland rice and sorghum) or other crops (e.g. sweet potato, melon, pineapple and castor bean) and legumes (e.g. soybean, green gram and peanut) (ECHO 2012). To control soil erosion, hedgerow intercropping agroforestry systems are composed of *Leucaena leucocephala*, *Gliricidia sepium*, and *F. congesta* planted as hedgerows, whereas agricultural crops are planted in between (Catacutan et al. 2017).

In the Morni Hills, north-east Haryana, the foothills of Siwaliks in northern India, some indigenous trees like *Acacia catechu*, *Cassia fistula*, *Emblica officinalis*, *Ziziphus mauritiana*, *Lannea coromandelica* and *Terminalia chebula* are retained as scattered trees and along the bunds in the terraced cropping systems (Fig. 2.7) to control soil erosion as well as to provide non-timber forest produce to the local community (Gupta and Kumar 2014).

In arid and semi-arid regions, all along the rivers and their tributaries, the soil is mostly alluvial and prone to soil erosion, and a net of gullies and deep ravines is formed. The phenomenon is more common along Indian rivers where about four million ha fall under ravines. Rehabilitation of ravine lands involves treatment of table and marginal lands (contributing runoff to the gullies) on watershed basis. It requires an integrated approach of using gullies according to land capability classes, soil and water conservation measures and putting land under permanent vegetation cover involving afforestation or agroforestry, horticulture, pasture and energy plantations (Chaturvedi et al. 2014; Dagar 2018a, b). Protection from grazing and afforestation with suitable species are the most effective measures for checking soil erosion and consequently ravine formation.

Dagar and Singh (2018) have recently compiled research carried out globally on greening of eroded habitats for livelihood and environmental security. In this compilation, Rodrigues (2018) reported the results of long-term experimentation in Brazil using low-cost vegetative, edaphic and mechanical techniques for gully rehabilitation after protecting the site from biotic interferences. The use of palisades to contain sediment exit was found effective which retained much of the sediment produced on the gully wall. Planting of shrub and herbaceous species also helped in

Fig. 2.7 A view of the terraced crop fields with significant tree components to control soil erosion in Morni Hills, foot hills of Siwaliks in northern India (Photo courtesy of SR Gupta)

generating cover; however, the ecological succession was underway. Guerra et al. (2018) gave an illustrated account of gully erosion and land degradation in five regions of Brazil, which affect socio-economic infrastructure of both urban and rural areas. Lal (2018) emphasized that medium and shallow ravines can be bulldozed for agricultural forestry land use and carbon sequestration in soil and biomass, with a technical potential of carbon sequestration of 2.6–5.3 TgC year^{-1}, as well as generating another income stream for farmers (US$300–640 million year^{-1}) and promoting the adoption of best management practices for both preventive and control measures. Dagar (2018a, b) while explaining formation, extent, ecology, biodiversity and control measures for ravine lands concluded that rehabilitation of these lands requires an integrated approach of using appropriate site-specific soil and water conservation measures and putting land under vegetation cover through afforestation, horticulture (mainly fruit trees), pasture and energy plantations depending upon the suitability class following watershed approach. Silvopastoral and fruit-based agroforestry systems involving species (including medicinal plants) of dry areas are the most appropriate options for rehabilitation of ravine lands.

2.5.2 Agroforestry for Degraded Drylands

GLASSOD database indicates that at world level, 349.6 million ha of land in arid zone are affected by light to moderate degree of soil degradation and 42.8 million ha by strong to extreme. Sand dunes are dominant land formation of principal hot arid zone (Africa accounts for 46.1% followed by Asia 35.5% and the rest 19.4% spread over in Australia and North America). The hot Indian arid zone (Thar Desert) is spread in 31.7 million ha. More than 34% (11 million ha) of the total area of Indian hot arid region is covered by drifting or semi-stabilized sand dunes, sometimes up to 100 m in height; however, their intensity varies from place to place. 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 windbreaks and mulch. Locally available brushwoods like *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* are being used frequently. In arid regions, *Prosopis cineraria*-based silvopastoral system has been found most suitable for sand dune stabilization in Thar Desert of Indian subcontinent. *Acacia tortilis*, *A. senegal*, *A. nilotica*, *Capparis decidua*, *Tecomella undulata*, *Colophospermum mopane*, *Calligonum polygonoides*, *Salvadora oleoides*, *Ziziphus nummularia*, *Carissa carandas* and *Haloxylon salicornicum* among woody species and *Cenchrus ciliaris*; *C. biflorus*; *C. setigerus*; *Lasiurus sindicus*; *Dactyloctenium sindicum*; species of *Aristida*, *Sporobolus*, *Eragrostis* and *Panicum* and many others among grasses are found useful for these habitats. Soni et al. (2016) have designated the silvopastoral systems in arid regions as lifeline for the poor stakeholders of the region. The vegetation for sand dune stabilization is highly drought tolerant with deep root system capable of extracting moisture from lower soil depths.

Many dry regions in India have shallow soil, particularly in the eastern and south-eastern parts of Rajasthan and Kutchh area of Gujarat. These areas have soil depth of 30–45 cm, and below this depth, there lies a calcareous *kankar* pan, which needs to be broken for tree plantations. A few tree species suitable for plantation include *Acacia senegal*, *A. salicina*, *A. jacquemontii*, *P. juliflora*, *Hardwickia pinnata*, *Capparis decidua*, *Grewia tenax*, *Ziziphus nummularia*, *Holoptelea integrifolia* and *Dichrostachys nutans*. Tewari et al. (2014) gave an illustrative account for livelihood improvement and climate change adaptations through agroforestry in hot arid environments of India.

Trees-based traditional cropping systems with *Prosopis cineraria*, *Ziziphus nummularia*, *Z. mauritiana*, *Tecomella undulata*, *Cassia siamea*, *Acacia tortilis* and *A. nilotica* play an important role in production system in hot arid regions of India (Dagar and Tewari 2017). These tree species act as shelterbelt for associated crops and also improve soil health. *Prosopis cineraria* (as is *Faidherbia albida* in Africa) is well-known for its role in improving crop productivity as well as

Fig. 2.8 General view of the cold desert and the agricultural landscape of Leh region in India (Photo courtesy of Pulkit Dagar)

conservation and amelioration of soil. Tewari et al. (2014) observed increase in available nutrients in association with trees proving that trees improve the soil health in arid ecologies.

Tewari et al. (2016) studied the traditional agroforestry systems in cold desert of Leh-Ladakh and observed that the land-based economy of these cold arid tracts comprised a crops-trees/shrubs-livestock-human continuum. A general view (Fig. 2.8) of cold desert of Leh region in India shows the land-use pattern of the area. The traditional agroforestry system of this region has been classified as among the possible "Globally Important Agricultural Heritage Systems (GIAHS)" by the Food and Agriculture Organization of the United Nations (FAO 2008).

The agricultural soils have been created artificially and maintained over centuries by repeated additions of manure, part of a continuous (re)cycling process of all agricultural products. This practice compensates the loss of organic matter due to erosion and the uptake of mineral nutrients by plants. Both private and community land support systems were fairly rich in the density of trees/shrubs and provide ample amount of wood for fuel and timber as well as tree leaves/tender twigs for livestock fodder. The maximum area was under potato followed by a fodder crop alfalfa. Wheat and barley, major staple crops, are sown only in one-fourth of total cultivable land. In all crops of the village, manure was the major input. Most of the trees and shrubs are found growing as boundary plantations, and *Populus balsamifera, P. ciliata, Salix alba, S. daphnoides, S. sclerophylla, Hippophae* *rhamnoides, Rosa eglanteria* or *Rosa rubiginosa* and *R. webbiana* are prominent species. Among fruit trees, *Malus pumila* and *Prunus armeniaca* are prominent. Both private and community land support systems are providing a large amount of energy in terms of fuel and leaf fodder supply, which indicates good health of these two components of the traditional agroforestry system in the cold desert of this region.

Agroforestry practices are major features of the land-use systems in the drylands of Eastern and Central Africa (Jama and Zeila 2005). Trees are used for a variety of purposes in both cropped lands and in livestock grazing systems. There are several traditional agroforestry systems in Tanzania that have been in practice for hundreds of years (Kitalyi et al. 2010). These traditional systems include the Chagga homegardens, the related Mara region homegardens known as Obohochere and the traditional Wasukuma silvopastoral system called *Ngitili*. These traditional systems make use of multilayered systems with a mixture of annual and perennial plants, which imitate natural ecosystems. The World Agroforestry Centre (ICRAF) in collaboration with national research institutions and other agencies has developed several technologies, which now benefit thousands of farmers in Shinyanga and Tabora regions of Tanzania (Kitalyi et al. 2010). Proven technologies include fertilizer trees and biomass transfer for soil fertility improvement, rotational woodlots, indigenous and exotic trees for food and health security, trees for livestock feed and trees for reclamation and enrichment of traditional land-use systems. In Tanzania, since the mid-1980s, local villages have restored 500,000 ha of woodlands within a five million ha landscape in the Shinyanga District, protecting the land and providing valuable non-timber forest products to local communities (www.wri.org/restorationdiagnostic, accessed on 11-06-2019). In the Hararghe highlands of eastern Ethiopia and other areas across SSA, *F. albida* is traditionally grown as a permanent tree crop with cereals, vegetables and coffee as under crops (Poschen 1986; Teketay and Tegineh 1991a, b; Mokgolodi et al. 2011).

For smallholder farmers in the East African region, Wekesa and Jönsson (2014) discussed common agroforestry practices, such as alley cropping, trees with perennial crops, windbreaks or shelter, contour trees, homegardens, shade trees and improved fallows. Silvopasture combines trees and livestock, which could involve planting of fodder trees, tree-based understory fodder production, hay making and/or grazing and cover crops for orchard floor management. Trees with a mix of crops and livestock constitute the agrisilvopastoral systems. Aquasilviculture is an agroforestry system that involves planting and/or maintaining belts of trees and shrubs in areas bordering lakes, streams, rivers and wetlands containing fish (Wekesa and Jönsson 2014).

Faidherbia albida trees are unique characteristics of the Sudano-Sahelian region of SSA, forming “parklands” (Bayala et al. 2014). In “parklands,” scattered mature trees constitute an integral component of crop and livestock production landscapes. Parklands play an important role in providing soil cover that reduces erosion and buffers the impacts of climate change. Rural communities in Burkina Faso, Mali, Niger and Senegal value more than 115 indigenous tree species for the livelihood benefits of their products and services (Faye et al. 2011). The parklands are the most common and improved agroforestry practices in these countries and combine crops, grasses, trees and livestock. Farmers maintain several indigenous tree species in parklands for food (e.g. *Adansonia digitata*, *Parkia biglobosa*, *Vitellaria paradoxa*, *Ziziphus mauritiana*); dry season fodder (e.g. *Balanites roxburghii, F. albida, Pterocarpus erinaceus*); wood for fuel, construction, household and farm implements (e.g. *B. roxburghii*, *Combretum glutinosum*, *Guiera senegalensis*, *Prosopis africana*); medicines; and environmental services such as shade, soil fertility improvement and soil/water conservation (Leakey 2012). The sale of these products contributes 25–75% of annual household revenue in Mali (Faye et al. 2011), with some having international market.

According to a study from the Sahel, the parklands buffer climate risk and sustain agricultural production (Bayala et al. 2014), indicating their importance under expected future climate change (Kassie et al. 2014). The parklands deliver multiple benefits, including various provisioning services and regulating ecosystem services, like soil nutrient replenishment, moisture conservation, carbon sequestration and soil erosion control (Sinare and Gordon 2015; Sida et al. 2018). In the Central Rift Valley of Ethiopia, scattered *F. albida* trees have been reported to improve wheat productivity significantly by buffering the crop against extreme temperature and facilitating increased water use efficiency (Sida et al. 2018).

Prosopis cineraria (as is *Faidherbia albida* in Africa) is well-known for its role in improving crop productivity as well as conservation and amelioration of soil. The Tree Growers' Co-operatives (Gujarat, India) promoted agroforestry on farmlands and wastelands by using fast-growing trees and tree-based oilseed crops. Tree-based traditional cropping systems are characterized with *Prosopis cineraria*, *Acacia leucophloea*, *Acacia nilotica* and *Acacia senegal* in semi-arid regions of District Mahendragarh, southern Haryana, India (Fig. 2.9); *Prosopis cineraria* with pearl millet is a common traditional agrosilviculture system of southern Haryana, India (Fig. 2.10a and b) and prevalent in the arid region Rajasthan.

2.5.3 Agroforestry Systems for Acid Soils

Acid soils occupy approximately 30% of the world's total land area (Zheng 2010), and it has been estimated that over 50% of the world's potential arable lands are acidic (von Uexkull and Mutert 1995). Aluminium (Al) in these soils is solubilized into ionic forms, especially when the soil pH falls to lower than 5. These ionic forms of Al have been shown to be very toxic to plants, initially causing inhibition of root elongation by destroying the cell structure. On the other hand, phosphorus (P) is easily fixed by clay minerals that are rich in acid soils, including various iron oxides and kaolinite, and hence rendering it unavailable for root uptake. Thus, increased

Fig. 2.9 Tree-based traditional cropping systems with scattered trees of *Prosopis cineraria*, *Acacia leucophloea*, *Acacia nilotica* and *Acacia senegal* in a semi-arid region of District Mahendragarh, southern Haryana, India (Photo courtesy of Dr. Vikram Singh)

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 India, acid soils cover an area of about 90 million ha (Sharma and Sarkar 2005), out of which about 7% are strongly acidic (pH $<$ 4.5); about 28% are moderately acidic (pH 4.5–5.5), and rest 65% are slightly acidic (pH 5.5–6.5).

In Latin America and the Caribbean, a large part of land consists of tropical forests with acid, infertile soils that are classified as oxisols and ultisols; a majority of these acid soils experience shifting cultivation or extensive grazing by beef cattle (Benites 1990). For well-drained acid soils of the humid tropics, some successful agroforestry option could be tree plantations, fruit tree-based production systems with intercropping, alley cropping and improved fallows (Benites 1990).

The majority of the soils in the humid tropics are acid and infertile (Szott et al. 1991). Agroforestry systems are the most appropriate forms of sustainable, productive management of soils in the humid tropics because perennial woody vegetation can recycle nutrients, maintain soil organic matter and protect the soil from surface erosion and runoff (Nair 1984). Based on investigations at Yurimaguas, Peru, Szott et al. (1991) indicated that alley cropping, managed fallows and fruit crop systems

Fig. 2.10 (**a**) Tree-based traditional system of *Prosopis cineraria* with pearl millet (*Pennisetum typhoides* at growing stage) in a semi-arid region of southern Haryana, India (Photo courtesy of Dr. Vikram Singh). (**b**) Tree-based traditional system of *Prosopis cineraria* with pearl millet (*Pennisetum typhoides* at maturity) in a semi-arid region of southern Haryana, India (Photo courtesy of Dr. Vikram Singh)

are potentially useful agroforestry systems for acid, infertile soils in the humid tropics as alternatives to or improvements of shifting cultivation. Several acid-tolerant, fast-growing, coppicing hedgerow species have been identified: *Inga edulis*, *Erythrina* sp., *Cassia reticulata* and *Gliricidia sepium*. Fruit crop production systems established with a low-input upland rice-cowpea rotation and followed by a legume cover crop seem highly promising for the region and as a way to move from shifting cultivation to settled farming.

In India about, 6.5 Mha land area is covered by strongly acid soils (pH < 5.5), mostly in states of Uttarakhand, Himachal Pradesh, Assam, Tamil Nadu and Kerala. The acid soils suffer due to lack of calcium and magnesium and in some cases due to aluminium and iron toxicity. In north-eastern states of India, more than 90% of the land is affected by soil acidity of varying degrees which have restricted the crop choice in more than 70% of gross cropped area to cereals mainly the rice (Jehangir et al. 2013). In north-eastern Himalaya regions, 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 and tuber crops like turmeric, ginger, *Colocasia* and taros make successful and sustainable agroforestry systems, which besides providing good economic yields also ameliorate soil by fixing nitrogen and organic matter.

2.5.4 Agroforestry for Salt-Affected and Waterlogged Soils

Salinity-afflicted landscapes, which now occupy nearly a billion ha globally (about 7% of land area) (Wicke et al. 2011), originated as a result of either natural geological phenomena or anthropogenic factors (secondary salinization). The excessive irrigation in agriculture has, mainly, contributed to the increasing problems of secondary salinization, alkalization and waterlogging (Szabolcs 1994; Rengasamy 2006; Qadir et al. 2007; Dagar and Minhas 2016). During the past two decades, interesting research and development work has been carried out on reclamation forestry on salt-affected landscapes. Technologies of tree plantation have been evolved, and many salt-tolerant species have been evaluated and identified, particularly in the Indian subcontinent and Australia. Prominent agroforestry systems for rehabilitating salt-affected lands in India, Central Asia and Western Australia include agrisilvicultural, silvopastoral and fruit-based agroforestry systems, trees for bio-drainage, energy plantations, halophytic plants to remediate soil and agroforestry for dryland salinity (Wicke et al. 2013; Gupta and Dagar 2016a, b; Dagar and Minhas 2016). To address the interest of arid and semi-arid regions to improve bio-saline agriculture, scientists have contributed towards developing technologies of growing halophytes in saline habitats and with use of saline water for irrigation (Dagar and Minhas 2016). This has been achieved through domestication and sustainable use of halophytic plants for food, fodder, medicine and reclamation purposes.

2.5.5 Revegetation and Rehabilitation of Mine Spoils

The major purposes of revegetating a mining site are to control sediment erosion and transport, enhance habitat and provide viable habitats for species that are in decline. The mining for various purposes leads to deterioration of the site to the extent that no biomass can be produced at the mined site. The process of vegetation development on these sites begins naturally through colonization by the species found in surrounding areas. Artificial seeding of fast-growing native grasses may accelerate development of vegetation, improve soil fertility and moisture retaining capacity, stabilize the slopes and encourage natural invasion of native tree and shrub saplings. Plantation of mixed stress-tolerant tree species may be undertaken after 2–3 years of growing grasses. Tree plantations can play an important role in restoring productivity, ecosystem stability and biological diversity of degraded areas due to mining (Singh et al. 2002). On mine spoils of the Singrauli coal field in Madhya Pradesh, India, *Albizia lebbeck* and *A. procera* have shown good restoration potential (Singh et al. 2004).

In Amarkantak region of India, successful attempts were made to rehabilitate bauxite mined area by planting *Eucalyptus camaldulensis, Grevillea pteridifolia*, *Pinus caribaea* and *Acacia auriculiformis*. Dhyani et al. (2007) reviewed some case studies of afforestation of mine wastelands in India, while Chaturvedi et al. (2014) reported different plant species suitable for revegetation of different types of mine spoils. The studies on mine spoils show that ground seeding of the mine spoils with suitable tree and grass species in combination with NPK fertilization can promote plant growth and increase biomass production (Chaturvedi and Singh 2017).

During the last two decades, considerable progress has been made on post-mining landscape restoration in Africa using physical, chemical and biological techniques (Festin et al. 2019). The various biological methods have shown encouraging results identifying plant species suitable for phytoremediation, using organic amendments to promote passive restoration of mine wastelands and studying growth response of planted species. Festin et al. (2019) have indicated some successful cases of large-scale post-mining restoration practices in Africa, which include restoration of limestone quarries in Kenya, sand mining tailings in South Africa and gold mine wasteland in Ghana (Siachoono 2010; Cooke and Johnson 2002; Tetteh et al. 2015a, b). In Kenya, large-scale ecosystem restoration on exhausted quarries at Haller Park, Bamburi, was started in 1971 by planting 26 tree species on 2 km^2 areas of open quarries (Siachoono 2010). By applying the topsoil application method to facilitate natural succession and establishment of indigenous dune forest, over 400 ha non-toxic sand tailings have been reclaimed since 1978 in South Africa (Cooke and Johnson 2002). A combination of physical, chemical and biological methods has been carried out to restore gold mine wasteland by AngloGold Ashanti at the Iduapriem mine at Tarkwa, Ghana (Tetteh et al. 2015a, b).

2.5.6 Silvopastoral Systems on Degraded Lands

Silvopastoral systems (SPS) are agroforestry arrangements that purposely combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses (Murgueitio et al. 2011). Silvopastoral systems are part of traditional farming systems throughout Latin America and the Caribbean for the various ecological benefits, including sustainability.

The main SPS comprises (1) scattered trees in pasturelands; (2) timber plantations with livestock grazing areas; (3) pastures between tree alleys, windbreaks, live fences and fodder banks with shrubs; and (4) intensive silvopastoral systems (Murgueitio et al. 2011; Chará et al. 2018). Agroforestry can diversify and increase agricultural production while also providing land users with other economic, social and environmental benefits. Chará et al. (2018) have discussed the main characteristics and advantages of silvopastoral systems regarding production and benefits for the environment and climate and their contribution to the SDGs on the basis of ten case studies in diverse contexts in Colombia, Mexico and Argentina, with a focus on land productivity, meat and milk production and economic performance at the farm level.

Varsha et al. (2019) have studied different fodder production systems in a warm humid climate of southern India. The systems were composed of 2-year-old silvopastoral systems and monoculture plots of fodder grass, tree and herbaceous legume and one control plot with natural grass vegetation for 2 years. These researchers reported that carbon stocks were significantly higher for mulberry (*Morus alba*) monoculture (174.84 Mg ha^{-1}), followed by tier two hybrid Napier (*Pennisetum typhoides* × *P. purpureum*) + mulberry (147.67 Mg C ha^{-1}), which accumulated 11–13% more carbon than tier three silvopasture and hybrid Napier monoculture systems (Varsha et al. 2019).

2.6 Environmental Services of Agroforestry

Forests and trees are vital land uses for restoring degraded landscapes and for providing environmental services such as carbon sequestration, watershed protection and biodiversity conservation. Agroforestry technologies can be applied to rehabilitate or restore degraded lands from agriculture, soil erosion, deforestation, rangeland degradation, mining sites and overextraction at various scales, from plot to farm level to large agricultural and farming enterprises. Agroforestry has both productive and service functions; e.g. a range of products, including fuelwood, fodder, timber and medicinal products, serve to diversify the outputs from agroforestry systems (Young 1997; Nair 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). These yield increases have been shown to reflect multiple ecosystem services provided by the trees. 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, providing habitat for pollinators and seed dispersers and climate regulation. 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 and 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.

The role of agroforestry for promoting climate change mitigation and adaptation, conserving biodiversity, improving soil fertility, enhancing carbon sequestration and improving livelihood security is briefly discussed in the following sections.

2.6.1 Climate Change Mitigation and Adaptation

Agroforestry systems have attracted special attention in climate change mitigation and adaptations. However, the site-specific nature of these systems and lack of uniformity in carbon sequestration estimation methods make it difficult to compare the reported results. Nair (2012a, b), for convenience of comparative analysis, grouped the systems in five subgroups—tree intercropping, multi-strata, protective, silvopasture and tree woodlots—and global areas under each are estimated at 700, 100, 300, 450 and 50 million ha, respectively. Tillage, crop residue management and plant diversity are reported as the major management operations that influence the role of land-use systems in climate change mitigation (Nair 2012a, b). Based on SWOT analysis, it was concluded that existing multi-strata and tree-intercropping systems will continue to provide substantial climate change mitigation benefits. Large-scale initiatives in grazing land management, working trees in drylands and establishment of vegetative riparian buffer and tree woodlots are promising agroforestry pathways for climate change mitigation and adaptations.

In recent times, atmospheric concentration of carbon dioxide has increased from pre-industrial levels of 280 ppm to about 414.41 ppm on 10 June 2019 at the Mauna Loa Observatory in Hawaii, the United States. The increasing concentration of carbon dioxide in the atmosphere is important because of its heat-absorbing properties. Averaged over all land and ocean surfaces, global temperatures have warmed by 0.85 °C (0.65 to 1.06 °C) over the period 1880 to 2012 (IPCC 2014). The increased CO_2 levels in the atmosphere are predicted to have pronounced human impact on terrestrial and marine ecosystems (IPCC 2014).

Agriculture is globally one of the largest emitters of greenhouse gases (GHGs). However, intercropping trees with crops can transform agriculture into a net sink of GHGs. Estimates indicate that agricultural land converted to agroforestry has the potential to annually sequester 27.2 ± 13.5 Mg CO_2eq ha^{-1}, at least for the first 14 years after establishment (Kim et al. 2016). The global mitigation potential, based on the assumption that 20% of the world's 630 million ha of unproductive agricultural land is suitable for agroforestry, accounts for 3.4 ± 1.7 billion Mg CO_2eq year^{-1} (Kim et al. 2016). Total annual global GHG emissions in 2016 were estimated at about 51.9 billion Mg CO_2eq (UNEP 2017).

Agroforestry can add a high level of diversity on degraded lands with an accompanied increased capacity for supporting numerous ecological and production services that impart resilience to climate change impacts (Verchot et al. 2007; Schoeneberger et al. 2012). The mixing of woody plants into crop, forage and livestock operations provides greater resilience to the interannual variability through crop diversification as well as through increased resource-use efficiency (Olson et al. 2000). Climate change adaptation refers to the use of a global change scenario to estimate the impact of global change on the system of interest and, then, undertake such strategies that adapt the system to these global changes. For example, farmers can vary the planting date or switch to different crop types or develop new crop types (Steffen et al. 2004). Trees used in agroforestry systems also provide a number of ecosystem services, such as erosion control, flood control and pest control, all important for resilience to climate change (Verchot et al. 2007).

Using long-term carbon sequestration rates for natural forest, plantations and agroforestry, Lewis et al. (2019) showed that restoring natural forests over 350 million ha of land removes 42 billion Mg of carbon by 2100, whereas using current pledges for plantations (45%), natural forests (34%) and agroforestry (21%) applied to the whole area reduces this to 16 billion Mg of carbon by 2100, assuming that all new natural forests are protected. The commercial monocultures can only sequester just 1 billion Mg of carbon when planted across 100% of the area.

Recently, the Intergovernmental Panel on Climate Change (IPCC) report suggests that an increase of one billion ha of forest will be necessary to limit global warming to 1.5 °C by 2050 (IPCC 2018). Bastin et al. (2019) have used direct measurements of forest cover to generate a model of forest restoration potential at a global scale and assessing the role in climate change mitigation. This study showed that ecosystems could support an additional 0.9 billion ha of canopy cover excluding existing trees and agricultural and urban areas. According to these workers, more than half the potential to restore trees could be found in just six countries including Russia, the United States, Canada, Australia, Brazil, and China. The restored woodlands and forests could store 205 Gt C if allowed to mature to a similar state of existing ecosystems in protected areas (Bastin et al. 2019). Further, these workers argued that if most of this additional carbon was accumulated from the atmosphere, there is possibility of reaching this maximum restoration potential (Bastin et al. 2019) and reducing a considerable proportion of the global anthropogenic carbon burden (~300 Gt C) (IPCC 2018). Thus, ecosystem restoration remains 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 and urban forestry in mitigating climate change.

2.6.2 Conserving Biodiversity

Agroforestry has been identified as a tool to conserve biodiversity in both temperate and tropical regions. The advanced landscape scale agroforestry system approach has a focus on establishing stronger link between AFS and biodiversity conservation (McNeely and Schroth 2006). Agroforestry systems play vital roles in biodiversity conservation by (1) providing additional habitats for species that can tolerate a certain level of disturbance; (2) preserving germplasm of indigenous and threatened species; (3) reducing the rates of conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems; (4) establishing connectivity by creating corridors between habitat remnants and the conservation of area-sensitive floral and faunal species; and (5) providing other ecosystem services, such as erosion control and water recharge, thereby preventing the degradation and loss of surrounding habitat (Jose 2012). 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 multispecies vegetation of AFS (Udawatta et al. 2019).

Agroforestry can significantly improve ecosystem services (ES) and enhance biodiversity conservation on degraded agricultural land and deforested areas (Chazdon 2008; Coelho 2017). Only a few studies have quantified the effectiveness of agroforestry systems to recover biodiversity and provision of ecosystem services in degraded areas (Santos et al. 2019; Torralba et al. 2016; Shimamoto et al. 2018). In a meta-analysis conducted in Europe, agroforestry systems showed a significant positive effect on biodiversity conservation and ES provision when compared with conventional systems, specifically in relation to nutrient cycling, biodiversity and erosion control (Torralba et al. 2016). The effects of different types of agroforestry systems on biodiversity and ES have been quantified, using a meta-analysis, in the Brazilian Atlantic Forest, a hotspot of biodiversity (Santos et al. 2019). Agroforestry systems provide up to 45% and 65% more benefits for biodiversity and ES levels, respectively, as compared to conventional production systems; however, these benefits differ according to the type of agroforestry system (Santos et al. 2019). A biodiverse agroforestry system is the best option to enhance biodiversity and ES in degraded areas that support environmental public policies focused on environmentally friendly land management practices and forest landscape restoration techniques (Santos et al. 2019). In a plant species diversity study in Nicaragua, Sistla et al. (2016) reported that secondary forest and agroforestry systems had greater food and medicinal value than the pasture.

The contribution of trees to the conservation of biodiversity and ecological functions, underpinning selected ecosystem services, has been evaluated across six agroforestry and tree cover transition in tropical/subtropical forest zones in Southeast Asia, China, Mexico, Kenya and Uganda (Barrios et al. 2018). These workers found that increased tree cover resulted in 53% increase in tea crop yield, maintained populations of crop pollinators and contributed to as much as 86% lower incidence of coffee berry borer. However, shade trees also caused negative effects through increased incidence of white stem borer and lace bugs, with a significant negative impact on endangered tree species in agroforestry and tree cover transition compared with forests. Thus, managing trees for ecosystem services in agroforestry systems needs greater understanding of the morphology and functioning of tree species in relation to different socioecological conditions (Barrios et al. 2018).

Pollination is one of the essential ecosystem services that has received widespread attention of workers. Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee (Klein et al. 2007). As much as around 35% of crops depend on insect pollination (HLPE 2017). In a fragmented landscape, agroforestry systems are, therefore, important habitats for pollinators (HLPE 2017), and the presence of more pollinators can lead to increased yields, especially for smallholder farmers.

2.6.3 Soil Fertility Improvement

Agroforestry systems have favourable effects on 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. Soil improvement in agroforestry systems is linked to biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, building up soil organic matter from aboveground and belowground parts of plants, increasing soil microbial activity, improving soil enzyme activity and enhancing activity of arbuscular mycorrhizal fungi (see Dollinger and Jose 2018 and references cited therein). Many studies have demonstrated that soils under trees in agroforestry systems have higher levels of organic carbon and mineralizable nitrogen, phosphorous, potassium and calcium than soils beyond the influence of trees. Agroforestry can also have a positive impact on soil microbial biomass and the diversity of soil microfauna (e.g. earthworms) (Rodrigues et al. 2015). Many studies have been conducted in Africa where fertilizer trees were grown in association with field crops, such as maize in rain-fed areas, which helped in increasing crop yield significantly (see Chaps. 3–10 in this volume), but only a few studies have addressed the effects of agroforestry trees on the microflora composition (Akinnifesi et al. 2010). In most agroforestry studies in sub-Saharan Africa, the belowground biodiversity has been found to increase, which correlated well with increasing crop yields and improved soil fertility (Kuyah et al. 2016).

There is a growing body of information on the role of *F. albida* trees in crop production and maintaining soil health (Bayala et al. 2012; Sileshi 2016). The influences of *F. albida* on soil and primary productivity are generally dependent on the size of trees, large trees exerting greater influence than small ones (Sileshi et al. 2014; Sileshi 2016).

There are several studies on the effects of silvopastoral systems on the physical, chemical and microbiological properties of the soil. The shrubs and trees in the SPS add layers of vegetation capable of transforming solar energy into biomass, which includes the formation of roots that penetrate deeper soil layers, from where they extract nutrients and water (Nair 2011). The greater number of strata also generates more abundant and heterogeneous biomass that is deposited on the soil in the form of leaves, branches, fruits, resins and exudates with important effects on nutrients, organic matter and biota (Vallejo et al. 2010). These benefits are complemented by the effect of nitrogen-fixing trees and shrubs and other associations between trees and microorganisms that increase the availability of vital nutrients for the production of biomass (Malchair et al. 2010).

2.6.4 Carbon Sequestration

Incorporating trees on land leads to an increase in soil organic carbon (SOC) stocks (Haile et al. 2008; Nair et al. 2009). de Stefano and Jacobson (2017) reported that compared with forest and uncultivated/other land uses, agroforestry revealed a significant and positive effect on SOC stocks at 0–30 and 0–100 cm soil depths. Nair et al. (2009) and de Stefano and Jacobson (2017) ranked SOC stocks as forests > agroforests > tree plantations > arable crops. The findings by de Stefano and Jacobson (2017), based on meta-analysis, suggest 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 agrosilvopastoral systems, forest to silvopasture, forest plantation to silvopasture and uncultivated/other land uses to agrisilviculture (de Stefano and Jacobson 2017).

Ramos et al. (2018) quantified the above- and belowground C stock and their distribution at the landscape scale in two oil palm- and cacao-based agroforestry systems in Brazil. They estimated greater aboveground carbon in litter and living biomass in an oil palm and cacao than in an oil palm herbaceous system. The aboveground carbon pool showed heterogeneous distribution in the landscape; SOC pool was the greatest pool of C irrespective of the system's design. 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 homegardens, and evaluated changes in AFS and adjacent control cropland or pasture. Mean soil C stocks in AFS (one meter soil depth) were 126 Mg C ha^{-1}, which is 19% more than cropland or pasture.

Cardinael et al. (2018) have presented a set of tier one coefficients for biomass carbon storage for the eight main agroforestry systems, including alley cropping, fallows, hedgerows, multi-strata, parklands, shaded perennial crop, silvoarable and silvopastoral systems, disaggregated by climate and region. In general, conversion from croplands to agroforestry systems resulted in increased SOC stock; however, variations were found to be large. The SOC storage rate depends on the various agroforestry system characteristics, such as tree density, age and species and management interventions (Kim et al. 2016), including pruning, soil tillage and fertilization (Feliciano et al. 2018). The amount of C input to the soil is probably one of the main factors explaining increased SOC stocks in croplands converted to agroforestry (Cardinael et al. 2018).

Recent findings indicate that conversion from forests to agroforestry systems generally resulted in SOC loss (Chatterjee et al. 2018; de Stefano and Jacobson 2018; Feliciano et al. 2018; Shi et al. 2018). Globally, conversion from grasslands to agroforestry systems did not improve SOC stocks. However, converting degraded grasslands to silvopastures could increase SOC stocks (Kaur et al. 2002a, b; Mangalassery et al. 2014; Kumari et al. 2018).

2.6.5 Improving Livelihood Security and Income Generation

In developing countries, most rural poor are smallholders practising low-input agricultural practices. Under these conditions, agroforestry can play an important role to improve the livelihoods of these people by producing food (e.g. fruit, nuts, edible leaves, sap and honey), fodder, timber, fuelwood, fibres and medicines (Hillbrand et al. 2017). Agroforestry can improve food and nutrition security by supporting staple-crop production along with edible tree products for home consumption, raising farmer incomes through the sale of tree products and surplus staples, producing fuelwood for cooking and heating and supporting pollination services, which are essential for the production of some food plants (Jamnadass et al. 2013). Trees like *Moringa oleifera*, which is considered to be tree of life as its all parts are highly nutritive and consumed, are boon for poor people. Other homestead fruit trees such as *Psidium guajava*, *Emblica officinalis*, *Mangifera indica*, *Syzygium cumini* and *Ziziphus mauritiana* are highly nutritive and commonly grown. Thus, many agroforestry products have the potential of a wide range of lesser-used indigenous foods found in different agroforestry systems that are often richer than staple crops in micronutrients, vitamins, fibre and proteins (see chapter by Dagar et al. in this volume). The leaves, fruit and other parts of many species of trees can serve as fodder for livestock especially in dry seasons when other sources of forage are not available. In a review summary of 94 studies from sub-Saharan Africa, Akinnifesi et al. (2010) concluded that using nitrogen-fixing trees increased yields up to several hundred percent and significantly improved food security. Jemal et al. (2018) analyzed the potentials of local agroforestry practices for food and nutrition security for smallholders in the Yayu Biosphere Reserve of south-western Ethiopia. Homegarden, multistorey coffee system and multipurpose trees on farmlands are the predominant agroforestry systems in Yayu. Multipurpose trees on farmlands are used mainly for food production, multistorey coffee system for income generation and homegarden for both. The 127 useful plant species identified in all three agroforestry systems represent 10 major plant utility groups, mostly producing food, fodder, fuel, coffee shade, timber, non-timber forest products and medicinal uses (Jemal et al. 2018).

Several trees, shrubs, herbs and climbers yield a substantial quantity of food materials which are used by the rural poor and particularly by tribal people. About 213 species of large and small trees, 17 species of palms, 128 species of shrubs, 116 species of herbs, 4 species of ferns and 15 species of fungi, mostly found in India, are known to yield edible food materials (Solanki 1981). Homegardens are the best example to support the view that these help rural people by supplementing the nutrients in the form of fruits, green vegetables, fish, eggs and other livestock products. Small ruminants are almost solely dependent on tree fodder obtained from agroforests or trees outside forests. Similarly, khejri (*Prosopis cineraria*) in arid regions of Indian subcontinent and *Faidherbia albida*-based agroforestry systems in Southern Africa and coconut (*Cocos nucifera)*-based homegardens in humid regions are the lifeline of the poor farming communities.

Agroforestry can contribute to reducing poverty by generating income. Farmers receive higher returns on their labour and diversify their income sources through the increased production of agricultural and forest goods. Agroforestry renders higher income to the farmer per unit area of land than the sole agriculture or forestry. Several studies in different parts of the world suggest that agroforestry is more profitable to farmers than agriculture or forestry for a particular area of land, particularly in dry ecologies (see Chap. 3 by Dagar et al. in this volume). Silvopastoral systems are highly remunerative because of dairy and other animal products and generate additional income when trees and tree products are harvested. The recognition of the ecosystem services provided by agroforestry offers a potential new source of income or other benefits for farmers through the establishment of incentives (either financial or in kind) (FAO 2013).

2.7 Conclusions

Agroforestry research now has provided useful technological and policy innovations that are rapidly spreading in Africa, Asia, Latin America and more recently in several developed countries. Now, agroforestry is considered not only for sustainable production system but also a problem-solving science. For example, agroforestry systems are playing a vital role for rehabilitation of degraded lands, mitigating climate change through carbon sequestration, employment generation and food and nutrient security. Agroforestry options have been found practicable in rehabilitation and biological reclamation of degraded lands prone to water and wind erosion including sand dunes; acid sulphate soils of humid regions characterized by low pH, toxicity of aluminium and iron and deficiency of nutrients; salt-affected sodic and saline soils; and waterlogged saline soils. For checking wind erosion, windbreaks and shelter belts involving appropriate species, which require less water and possess deep root system, have been established in drylands; the trees and shrubs play major role in improving efficiency of nutrient cycling in the system.

For agroforestry to succeed, it requires a systems perspective that can be readily integrated into landscape approaches. At the field scale, agroforestry interventions aim to maximize multiple benefits, such as improving soil health, conserving biodiversity and providing minor forest produce, while minimizing negative interactions between trees and crops. Restoration is widely acknowledged as a way of reversing degradation processes and increasing the contributions of ecosystems and landscapes to livelihoods, land productivity, environmental services and the resilience of human and natural systems. Many countries, including Costa

Rica, Niger, South Korea, China, India and Ethiopia, have achieved success through forest landscape restoration.

Agroforestry should be looked upon as a means for improving the socio-economic conditions of the rural poor and the main plank of integrated rural development programmes. To increase fuelwood, timber and fodder production, agroforestry programmes should be adopted at landscape level. This practice will ensure the balanced economy of woodlots for the rural areas. With a proper management of inputs, the productivity can be increased manyfold. With a proper management of inputs, the productivity can be increased manyfold. The main component of the production technology includes proper tillage operation, appropriate lopping, grazing and tree density, application of bio-fertilizers, use of biotechnology, genetic improvement of existing tree species for better yields and the selection of the most economically suitable species. Revegetation of the wastelands and arid areas to meet both ecological and social challenges requires development of sites with specific packages of practices for promoting the agroforestry and silvopastoral systems in the region. Profitable agroforestry is possible if appropriate technologies and know-how are used judiciously. The development and upscaling of traditional and improved agroforestry systems also need an enabling environment, such as clear land and tree tenure, a strong legal framework, availability of agroforestry product value chains and involvement of the various stakeholders.

There is a need to improve capacity of stakeholders to design AFS for (1) supporting sustainability of crop production and restoration of biodiversity and other ecosystem services at plot and landscape scales, (2) identifying best practices of diverse AFS with partners in the field to improve food production and other ecosystem services, (3) surveys of local knowledge and practices, (4) knowledge on soils and land use of degraded landscapes for a better understanding of soil properties and (5) potential carbon sequestration. Soil organic carbon is a crucial link between land restoration, agricultural productivity and climate change adaptation and mitigation. Agroforestry provides opportunities to meet the livelihood security to poor and landless farmers and mitigate climate change and several other ecological services. For a successful action plan, farmer-friendly policies are needed, both at national and regional levels.

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Part II

Tropical Agroforestry: Arid and Semiarid Regions

3 Agroforestry to Enhance Livelihood Security in Africa: Research Trends and Emerging Challenges

Jagdish Chander Dagar, G. W. Sileshi, and F. K. Akinnifesi

Abstract

Africa faces intricate challenges including severe shortage of food, fuelwood and fodder primarily due to increasing human and livestock population and subsistence agriculture. Deforestation, declining soil fertility and soil erosion are the crucial indicators of land degradation. Most of the dry regions experience food shortage due to low crop yields in the nutrient-depleted soils. Farmers are forced to extend cultivation to marginal and erosion-prone soil clearing the forests. Continuous cultivation has replaced the traditional shifting cultivation and fallow systems, which have been practised to regenerate soil fertility in most parts of Sub-Saharan Africa (SSA). Following the inception of the International Centre for Research in Agroforestry (ICRAF) in 1987, traditional agroforestry systems have been carefully documented through the diagnosis and design phase in the late 1980s, and new agroforestry innovations were tested at research stations and on farms mostly in tropical countries across the world. Many improved agroforestry options are now being disseminated and used by resource-poor farmers in

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SSA. In this chapter, both traditional and improved agroforestry systems in SSA, which form a basis of food security for resource-poor farmers, have been described briefly.

Tracing the linkages and prospects of agroforestry systems to enhance food security, attempt has been made to report existing status of indigenous forest and fruit tree species, domestication of indigenous fruit trees, utilisation and nutritional quality of tree products and fruit transformation into commercial products as reported in various studies. In this review, we highlight the state of research on different agroforestry systems, the role of trees in amelioration/reclamation of degraded lands, soil and water conservation, hydrological benefits, microclimatic modifications and biodiversity conservation. In addition, we identified constraints, issues of agroforestry adoption and technical areas still requiring scientific inputs. In a synthesis of research trends and emerging challenges, agroforestry has tremendous potential for food security, increasing land productivity and enhancing livelihood security particularly in degraded and dry regions of SSA. The widespread adoption of agroforestry technology supported by continued participatory research and dissemination can be instrumental to achieve the goals of poverty alleviation, food security, soil conservation and environmental sustainability in different regions of Africa, particularly in the scenario of climate change.

Keywords

Shifting cultivation · Taungya · Rotational woodlots · Homegardens · Community agroforestry · Domestication · Indigenous fruit trees · Fertiliser trees

3.1 Introduction

Rapid population growth coupled with rural poverty, youth unemployment, outmigration and urban growth will continue to drive changes in food and agricultural systems in SSA in the next decades. Nigeria, Ethiopia, Egypt, Democratic Republic of Congo and South Africa are the most populous countries. An estimated 821 million people, approximately one out of every nine people in the world, are undernourished (FAO 2018). According to available data, the number of people who suffer from hunger has been growing in almost all regions of Africa (256 million). In Africa, about 20.4% of people are undernourished. Mounting evidence points to the fact that climate change is already affecting agriculture and food security, which will make the challenge of ending hunger, achieving food security, improving nutrition and promoting sustainable agriculture more difficult as envisaged under the Sustainable Development Goals. A heavy reliance of the people to rain-fed agriculture (crops and rangelands) makes rural populations more vulnerable. Furthermore, in arid, semi-arid and dry subhumid areas, the impacts of human activities aggravate conditions leading to desertification and drought. In those regions, diversified agriculture involving agroforestry-based cropping systems may help in increasing crop production and food security, reducing poverty and mitigating climate change.

Almost all the soil orders are found in Africa. The highly weathered and leached acid infertile soils and dry sands and shallow soils without horizon development with low fertility predominate the soil types in Africa. A new Soil Atlas of Africa has been published in 2014 (https://www.isric.org/projects/soil-atlas-africa). Africa has, by far, the greatest amount of hyperacid land (~705 million ha), mainly the Sahara Desert. Other dry lands include rangeland and rain-fed agricultural land, and only 6% of the farm lands of the continent is irrigated (www.ifpri.org/irrigating-africa). Land degradation and desertification are among the world's greatest environmental challenges. It is estimated that desertification affects about 33% of the global land surface and that over the past 40 years, erosion has removed nearly one-third of the world's arable land from production. Africa is particularly vulnerable to land degradation and desertification, and it is the most severely affected region. Desertification affects around 45% of Africa's land area, with 55% of this area at high or very high risk of further degradation (ELD Initiative and UNEP 2015), and the results indicate that in the next 15 years, starting from 2016, inaction against soil erosion will lead to a total annual loss of NPK nutrients of about 4.74 million tonnes per year, worth approximately 72.40 billion PPP USD in present value, which is equivalent to 5.09 billion PPP USD per year.

In Africa, the forest cover is considered to be 624 million ha (600 million ha to be natural and rest planted), which is about 20.6% of the land area, and forest area is declining at the rate of 2.8 million ha per year [from 2010 to 2015 (http://www.southworld.net)]. Selective logging and clear cutting for timber, firewood, and agricultural land use; expansion of human habitats and urbanisation including infrastructure development and mining; and accidental fires and deliberate burning are the major reasons of deforestation. Declining soil fertility due to deforestation for expansion of agriculture is one of the root causes of low crop productivity. Due to rapid population growth and inequitable land distribution, the farmers now cultivate the same piece of land more frequently reducing the fallow phase to 1 or 2 years and in some cases cultivating every year, thereby exhausting the soil resources to support crop production. Without fertilisers and having no fallow period, productivity of food crops remains low, and many farm families cannot produce enough to feed themselves even during years of favourable rainfall. Drought and lack of dry season forages also constrain livestock production. At the same time, the native woodlands that provide timber, fuelwood, fruits, forage, medicine and other minor products for livelihood of rural people are overexploited or destroyed by intentional fires. The farmers in Africa must look for ways to overcome all these constraints to break out of the poverty cycle. They would have to adopt new techniques to improve the productivity of their lands and sustain their environment. Agroforestry may provide a set of viable options to solve the above-mentioned problems of poor small landholders.

Some of the traditional and improved agroforestry systems, constraints, methods of improvement in agroforestry systems and policy matters with special reference to African continent have been discussed here in this chapter.

3.2 Agroforestry Systems/Practices in Africa

Several traditional and improved agroforestry systems/practices have been often recorded in different agroclimatic situations across the world (Nair 1993; Akinnifesi et al. 2008a, b, c; Dagar 2014; Dagar et al. 2014a, b; Dagar and Minhas 2016; Dagar and Tewari 2016a, b, 2017a, b). A closer examination of the distribution of these systems in different ecological and geographical regions reveals that there is a clear relationship between the ecological characteristics of a region and the nature of the agroforestry systems of the region. For example, shifting cultivation, taungya, plantation-crop combinations, multilayer tree gardens and intercropping systems in humid low lands; silvopastoral systems, wind breaks and shelterbelts, multipurpose trees for fuel and fodder and multipurpose trees on farmlands in semiarid lowlands; and soil conservation hedges, silvopastoral combinations and plantation crop combinations in highlands have been listed and explained by many workers (Awodoyin et al. 2015; Dagar and Tewari 2017a; Dagar and Singh 2018). Some of the common agroforestry practices found in different regions of Africa have been described in the following sections in brief.

3.2.1 Shifting Cultivation (Slash-and-Burn Agriculture)

Shifting cultivation, one of the traditional agricultural practices, is followed in different agroecological conditions in various regions of the world. It refers to farming system in which land under natural vegetation (usually forests) is cleared by the slash-and-burn method, cropped with common arable crops for a few years and then left unattended while the natural vegetation regenerates. Traditionally, the fallow period is 10–20 years; recently due to population pressure, the fallow period was reduced to 3–5 years. The system is still the mainstay of traditional farming systems over vast areas of the tropical and subtropical Africa. Depending on the environmental and sociocultural conditions, the system is recognised by different names in the world. In Africa, it is addressed with names such as *masole* (Congo, Zaire river valley), *fang* (equatorial countries), *tavy* (Madagascar), *logan* (West Africa), *chitimene/chetemini* (Uganda, Zaire, Zambia, Zimbabwe, Tanzania, Malawi) and *proka* in Ghana (Okigbo 1985; www.jagaranjosh.com).

In the tropics, the system is dominant mainly in sparsely populated and lesser-developed area, especially in the humid and subhumid tropics of Africa and Latin America, and densely populated in Southeast Asia. Haokip (2003) mentioned that in the world, about 500 million people are estimated to practise shifting cultivation. Though exact figures about total area under shifting cultivation are not available, it is still applied in about 40–50 countries (Mertz 2009) and constitutes an important part of the 850 million ha of secondary forest in tropical Africa, America and Asia (FAO 2005).

Tropical humid forests during their growth accumulate huge quantities of nutrients in their vegetation, with a mature forest reaching steady-state values of 700–2000 kg N, 30–150 kg P and 400–3000 kg K, Mg or Ca ha^{-1} (Sanchez and

Palm 2002). The forest soil also contains large quantities of nutrients. Clearing of forests results in major disruptions of this process because large quantities of nutrients are removed from the system and nutrient cycles are disturbed. The magnitude of nutrient mining due to crop harvests in Africa is huge. Net losses of about 700 kg N, 100 kg P and 450 kg K ha^{-1} have been estimated for 100 million ha of cultivated land (Sanchez et al. 1995) in three decades. The dominant narrative recited by policy experts, nongovernmental organisations and many scientists is that this practice is a principal cause of deforestation in tropical Africa which is not always true (Ickowitz 2006). Recently, Heinimann et al. (2017) while exploring the global view of shifting cultivation estimated that these landscapes currently cover roughly 280 million hectares worldwide, including both cultivated fields and fallows, and in about 37% of tropical Africa, this form of cultivation remains widespread. Taungya, fallow cultivation and alley cropping are considered to be alternatives to shifting cultivation.

3.2.2 Taungya and Shamba Systems

The word 'taungya' originated in Myanmar, meaning hill (*taung*) cultivation (*ya*). Originally, it was the local term for shifting cultivation and was subsequently used to describe the afforestation method (Nair 1993). The system was later introduced into parts of India and later spread throughout Asia, Africa and Latin America. Wood and food production are immediate motivation of this system. In Jamaica, it is called as *agricultural contractors' system* and in Tanzania *the licensed cultivator system.* In Nigeria, taungya consisted of interplanting of young *Gmelina* (*Gmelina arborea*) and/or teak (*Tectona grandis*) with maize, yam or cassava. Farmers cultivate the land during the early phase of tree establishment until canopy closure, usually 2–3 years. Ojeniyi and Agbede (1980) found that the practice usually resulted in a significant increase in soil N and P, a decrease in organic C and no change in exchangeable bases and pH as compared with sole stand of *Gmelina*.

Oduol (1986) described a modified form of taungya called the 'Shamba system', which is being practised on state forestland in Kenya. Under this system, each participant agrees to work for the forest department for 9 months each year to clear bush cover from an area of about 0.5 ha. The farmer is allowed to cultivate crops (usually maize, potatoes and vegetables) for a period of 2–3 years with the sole right to all such produce. The forest department plants trees in the cleared land. Within 2 years after clearing, farmers are allowed four Shambas of 0.5 ha each. The success of this system may be attributed to four main factors (MacDicken 1990): availability of arable lands; the presence of a willing, land-hungry farm population; ready markets for surplus produce; and security against wild animals. The widespread of this system contributed roughly 16% of Kenya's maize production and about 38% of the nation's total potato production.

Chamshama et al. (1992) studying the suitability of Kilimanjaro Forest Plantation of Tanzania reported that during the early stages of forest plantation establishment, intercropping of young trees with food crops is beneficial in terms of tree survival, food crop production, financial income to the peasant farmers and reduction of forest plantation establishment costs confirming the sustainability of the system. In most of the taungya systems, erosion hazards, rather than soil fertility, are likely to pose the greatest soil management problems. Oluwadare (2014) after analysing select 100 farmers revealed that agricultural production under *taungya* farming in Nigeria was profitable and productively and technically efficient and ensured the production of choice economic trees that would guarantee continuous production of such trees. The technical efficiency of the taungya farms would improve with improved education and increased technical assistance in form of extension visits. All these studies confirm the sustainability of the system and security of livelihood of resource-poor farmers.

3.2.3 Rotational Woodlot System

Trees grown in rotational woodlots is a form of *taungya* system, except that the trees have soil fertility improvement attributes or are used as fodders and shade for livestock. Rotational woodlots are promising agroforestry options that can be used to address the problems of deforestation and shortage of wood energy. Woodlots are sole stands of trees planted on farms, communal lands or degraded lands to rehabilitate the land as well as provide products and services. Woodlots have become important in other parts of tropical Africa (Nyadzi et al. 2003).

The rotational woodlot involves growing of trees and crops in three phases: (1) an initial tree establishment phase in which trees are intercropped with annual food crop (s), usually maize; (2) a tree fallow phase in which cropping is discontinued because of canopy closure and increased shading; and (3) a cropping phase after felling the trees and harvesting of wood (Kwesiga et al. 2003; Nyadzi et al. 2003). Each of the phases is managed to provide products and services that have economic, social and environmental value. The trees benefit from land preparation and weed management primarily for the annual crops.

In Tanzania, trees could be managed as the traditional 'ngitili system' during the first 2–3 years of fallow phase, in designated areas enclosed for natural regeneration of vegetation for livestock sustenance, or as fodder banks (Nyadzi et al. 2003; Otsyina et al. 2004). After harvesting trees, crops can be grown between the stumps or coppices to exploit accumulated nutrients in the litter fall, leaves and branches. The coppiced shoots may be pruned to reduced competition for light during this second cropping phase and incorporated in the soil for manure or harvested as fodder. However, the coppiced shoots may be allowed to grow for another cycle of the tree fallow phase. The quantity of biomass produced by some tree species is depicted in Table 3.1.

Suitable trees species identified for the miombo ecozone of southern Africa include *Acacia crassicarpa*, *A. leptocarpa*, *A. auriculiformis* and *A. julifera*. These species are known to producing substantial amounts of fuelwood (Table 3.1). Likewise, in on-farm assessments in Tabora, Tanzania, *A. crassicarpa* woodlots produced high quantity of fuelwood ranging between 77 and 100 Mg ha^{-1} within

Table 3.1 Potential annual harvestable fuel produced by trees planted in woodlots, coppicing fallows and non-coppicing fallows (compiled from various sources)

Country	Site	Tree species	Tree age (years)	Quantity (Mg ha^{-1} year^{-1})	References
Tanzania	Mganga	*Acacia crassicarpa*	5	22.4	Otsyina (1999)
	Kiwango	*Acacia crassicarpa*	4	24	Otsyina (1999)
	Dotto	*Acacia crassicarpa*	4	19.5	Otsyina (1999)
	Sanania	*Acacia crassicarpa*	4	21.0	Otsyina (1999)
	Shinyanga	*Acacia nilotica*	7	1.2	Nyadzi et al. (2003)
	Shinyanga	*Acacia polyacantha*	7	10.1	Nyadzi et al. (2003)
	Shinyanga	*Leucaena leucocephala*	7	12.7	Nyadzi et al. (2003)
Zambia	Chipata	*Senna siamea*	3	10.7	Ngugi (2002)
	Chipata	*Leucaena leucocephala*	3	9.7	Ngugi (2002)
	Chipata	*Sesbania sesban*	3	8.0	Ngugi (2002)
	Chipata	*Gliricidia sepium*	3	7.0	Ngugi (2002)

Source: Sileshi et al. (2007)

6–7 years (Nyadzi et al. 2003), suggesting that using fast-growing trees in rotational woodlots can help reduce pressures on the natural forests and woodlands. Additional benefit from rotational woodlot with N-fixing legumes includes increased crop yields and fodder.

3.2.4 Improved Tree Fallows

The rate and extent of soil-productivity regeneration depend on the length of the fallow period, the nature of fallow vegetation, soil properties and management intensity. Bishop (1982) described an agro-silvopastoral system from Ecuador, in which 2 years of food crops were followed by 8 years of fallow consisting of *Inga edulis* interplanted with bananas and a forage legume. In Peru, biomass production from *Inga* was reported to be greater than that of herbaceous fallow, as well as equalling or exceeding the natural forest (Szott et al. 1991). Various approaches have been suggested as improvement and alternatives to shifting cultivation (Robinson and McKean 1992) and the importance of retaining or incorporating the woody vegetation into the fallow phase (even in the cultivation phase) as key to the maintenance of soil productivity. Long-term fallows of 20–30 years are no longer feasible, and shorter natural fallows up to 10 years do adequately replenish soil fertility. In modern times, improved or managed short-term fallows of 1–3 years have been developed in many regions to allow for rapid replenishment of soil fertility. Leguminous *Sesbania sesban*, *Tephrosia vogelii*, *Gliricidia sepium* and *Leucaena leucocephala* have been identified as the most promising N-fixing shrubs for this purpose (Kwesiga et al. 1999, 2005; Rao et al. 1999).

The techniques for integrating these species as short-duration planted fallows in rotation with crops to build up N-capital in farmers' fields are now in place. These fallows help farmers in increasing crop yield and replenishing soil fertility. In experiments conducted over a period of 15 years in Zambia, maize yields in three normal rainfall years after 2 years of *Sesbania* fallow averaged 5.6 Mg ha^{-1} compared to 2.0 Mg ha^{-1} in unfertilised continuous maize and 4.1 Mg ha^{-1} when maize was fertilised with 112 kg N ha^{-1}, 20 kg P and 16 kg K ha^{-1} (Kwesiga et al. 1999). Two-years *Sesbania* fallows produced 15 Mg ha^{-1} of fuelwood (Place et al. 2002) and required less than half the amount of labour needed for 1 ha of continuously cropped maize. Further, it was reported that high maize yields following such fallows are primarily due to increased organic matter input into the soil and nitrogen supply to crops (Barrios et al. 1996). In some other fallows in southern Africa, the increase in maize yield ranged from 40 to 317% over unfertilised control (Table 3.2).

In Zimbabwe, several planted tree fallow options, including *Acacia angustissima*, *Cajanus cajan* and *S. sesban*, were compared with grass fallow and continuous cropping with or without fertilisers (Mafongoya and Dzowela 1998). The tree fallows increased the subsequent maize yields over the control crops, maize after grass fallow and continuous maize without inorganic fertilisers. Financial results proved that these improved fallow systems were highly profitable. Planting *Sesbania sesban* for 2 years emerged as most profitable option. Of various species, *Tephrosia vogelii* was most preferred by farmers because it is both a soil improver and a pesticide (Kwesiga et al. 2003). *Cajanus cajan* was also ranked high because it provides food in addition to improving the soil. A number of species that could be established once and then managed for a long duration (>15 years) through coppicing included *Gliricidia sepium*, *Leucaena leucocephala*, *Senna siamea*, *Calliandra calothyrsus* and *Flemingia macrophylla*. *Sesbania sesban* triumphed over all the coppicing options as well as the controls with respect to increase in maize yields (Table 3.3) and suppression of weeds (Kwesiga et al. 2003).

Akinnifesi et al. (2010) reviewed several studies conducted both on-station and on-farm and synthesised the results in terms of improvements in soil physical, chemical and biological properties and crop yield in response to fertiliser trees. The yield increase due to nitrogen-fixing perennials was significantly higher as compared to without trees (Table 3.4). The major findings included (1) fertiliser trees added more than 60 kg N ha^{-1} per year through biological nitrogen fixation; (2) nutrient contributions from fertiliser tree biomass can reduce the requirement for mineral N fertiliser by 75%, translating to huge savings on mineral fertilisers; (3) fertiliser trees were also shown to substantially increase crop yield; and (4) fertiliser tree systems are profitable and also have higher net returns than the farmers' de facto practice, i.e. continuous maize cropping without fertiliser. Thus,

Table 3.2 Impact of improved tree/short-term shrub fallow-based options on maize yields at different sites in southern Africa

		Soil type			Yield	
Site	Rainfall (mm)	Mg ha^{-1}	Planted fallow	Control	Percentage increase	
Chipata, Zambia	950	Alfisols	2-years *Sesbania sesban*	Maize without fertiliser	3.8	317
			2-years *Cajanus cajan*		1.7	155
			2-years *Tephrosia vogelii*		2.1	191
Makoka, Malawi	980	Alfisols	2-years *S. sesban*	Grass fallow	2.8	255
Domboshawa, Zimbabwe	750		2-years *S. sesban*	Grass fallow	3.0	188
			2-years *C. cajan*		1.8	113
			2-years *Acacia angustissima*		1.0	63
Tabora, Tanzania	700	Ultisols	2-years *S. sesban*	Maize without fertiliser	2.0	120
			2-years *C. cajan*		0.5	50
Shinyanga, Tanzania	800	Vertisols	2-years *S. sesban*	Maize without fertiliser	0.5	40

Source: Kwesiga et al. (2003)

Table 3.3 Aboveground biomass at the end of 3-years fallow period and maize yields following tree fallows

Fallow species	Biomass (Mg ha^{-1})	Maize yield (Mg ha^{-1})
Sesbania sesban	23.5	5.6
Gliricidia sepium	20.5	3.8
Flemingia macrophylla	17.8	3.5
Leucaena leucocephala	29.0	3.7
Calliandra calothyrsus	11.5	2.6
Senna siamea	59.0	2.1
Grass fallow	17.2	2.2
Groundnut–maize rotation	–	3.1
Continuous maize without fertiliser	–	2.0
Continuous maize with fertiliser (112, 20 and 16 kg ha^{-1} year^{-1} N, P and K)	–	4.1
SED	8.8	0.33

Source: Kwesiga et al. (2003)

Table 3.4 Increase in maize yield (Mg ha^{-1}) with nitrogen-fixing trees as compared to the yield without trees

Tree species	Country	No. of sites	Yield (Mg ha^{-1})	Yield increase[a] (Mg ha^{-1})	Yield increase[a] Percentage increase
Gliricidia sepium	Malawi	5	3.9	2.9	345.6
	Tanzania	2	2.3	0.8	55.8
	Zambia	4	2.8	1.8	349.7
Sesbania sesban	Malawi	7	2.5	1.3	161.4
	Tanzania	2	1.2	0.7	171.4
	Zambia	9	3.2	2.2	480.0
	Zimbabwe	4	3.0	1.9	583.1
Tephrosia vogelii	Malawi	9	2.0	1.1	232.7
	Tanzania	2	2.0	0.9	80.1
	Zambia	8	1.7	0.8	198.4
	Zimbabwe	5	3.6	0.2	17.7

Source: Akinnifesi et al. (2010)

[a]Yield increase is the yield difference between the treatment (T) plot and the unfertilised control (C) plot, which is farmers' de facto practice. Percentage increase (%I) was calculated as follows: $\%I = 100((T - C)/C)$

the widespread adoption and scaling up of fertiliser trees can reduce the amount of mineral fertiliser needed, maintain the soil ecosystem and positively impact on the livelihoods of farm households in southern Africa.

With consistent efforts of many workers (Franzel et al. 2001; Amadalo et al. 2003; Kwesiga et al. 2005), farmers adopted successfully the short fallows of 2–5 years and could sustain the crop yields improving the soil properties in deforested and degraded areas. They raised one or more woody species in these fallows along with field crops. The woody species mostly shrubs included *Sesbania sesban*, *Tephrosia vogelii*, *Cajanus caja*n and *Acacia angustifolia* in eastern Zambia, Zimbabwe and southern Malawi; *Calliandra calothyrsus* in Kenya and Cameroon; *Leucaena leucocephala* in many African countries as alley crop; *Senna/Cassia siamea* and *Flemingia macrophylla* in Ghana; and *Acacia angustifolia*, *A. mangium*, *Inga edulis*, *Sclerolobium paniculatum*, *Gliricidia sepium* and *Leucaena leucocephala* in Tanzania, Nigeria and many other countries. Other species included *Tephrosia candida*, *Desmodium uncinatum*, *Crotalaria juncea*, *C. grahamiana*, *C. paulina* and *C. striata*. In many locations, herbaceous cover consisting of tropical *Canavalia ensiformis*, *Calopogonium mucunoides*, *Mucuna pruriens*, *Dolichos lablab*, *Macroptilium atropurpureum* and *Crotalaria* spp. is frequently grown to improve the fallow, which also control weed infestation. Recently, Sileshi et al. (2011, 2014) have given a comprehensive account of the fertiliser trees and their role in yield increase of crops such as maize when cultivated with these trees.

In the densely populated Shire Highlands of southern Malawi, farm sizes are extremely small (0.1–0.5 ha) with traditional maize cultivation without fertilisers and intercropping with legumes such as *Cajanus cajan* (Rao et al. 1999). In order to overcome the problem of replanting *Sesbania sesban* every year, *Gliricidia sepium* with an impressive coppicing performance was chosen as an alternative as management on the basis of its high (4%) foliage N content (Kwesiga 1994). It was planted evenly spaced (0.9–1.5 m) throughout the field and cut at 30 cm above ground such that no area was forfeited to the hedgerow. Long-term results showed that maize yield began to exceed those of maize planted alone with and without fertiliser by the third season after tree establishment, often doubling those of the control by the 4th year and subsequently. *Gliricidia* maintained foliage biomass at 2–5 Mg ha^{-1} per season during an 8-year period, without the need of replanting (Rao et al. 1999).

In parts of Zimbabwe, Tanzania and northern Zambia, biomass transfer (mulching or green leaf manuring using foliage of trees and shrubs cut and carried to cropping areas) is a traditional practice. The application of *Gliricidia* biomass to cabbage and onion in *dimbas* followed by growing a maize crop during the dry season was found to be profitable (Kuntashula et al. 2004). *Tephrosia vogelii* is a coloniser of wastelands in Malawi, and use of its biomass for crop production could be turned into a profitable venture (Kwesiga et al. 2003). In one well-conducted experiment in Zambia for degraded Acrisols, Chirwa et al. (2003) reported that mono-species fallows of *Sesbania sesban* (non-coppicing), were poorly adapted and *Gliricidia sepium* (coppicing) was superior to other species (*Leucaena leucocephala* and *Acacia angustissima*). At the end of 3 years, sole *G. sepium* fallow produced the greatest total biomass of 22.1 Mg ha^{-1} and added 27 kg ha^{-1} more N to soil than *G. sepium* + *S. sesban* mixture. The latter increased water infiltration rate more than sole *G. sepium*. Although sole *G. sepium* produced high biomass, it was *G. sepium* + *S. sesban* mixed fallow which resulted in 33% greater maize yield in the first post-fallow maize showing the superiority of the system.

Improved fallows are considered successful because of three major factors, viz. their effects on improving household welfare (livelihood); the various environmental services they provide (improve soil properties in terms of organic matter, higher infiltration rate, increased aggregates stabilising soil, carbon sequestration, etc.); and the development of an institutional mechanism, an adaptive research and dissemination network of government, NGOs and farmer organisations, to sustain adoption of the practice (TECA 2003). The crops and other food items are almost organic or with limited use of fertilisers and insecticides (produced from organic source like from leaves of *Tephrosia vogelii*) and also reduce pressure from woodlots. The main limiting factor in Africa is clearly the supply of germplasm of improved fallow species for large number of farmers ready to adopt the system. This must be overcome through large-scale seed orchards and nursery development and assistance from the government and policymakers.

3.2.5 Alley (Hedgerow) Cropping

Alley cropping, though considered a modern system, is not a new concept. During the 1930s, the Dutch colonial government introduced contour terracing using

Leucaena leucocephala hedgerows planted 3 m apart for erosion control and soil fertility improvement on the island of Timor in eastern Indonesia (Metzner 1982). The introduction initially was not accepted locally because in short time the plant colonised widely due to lack of management. During the 1970s, the International Institute of Tropical Agriculture (IITA) in Nigeria conducted investigations to assess the potential of intercropping woody species with food crops as a land use system to manage fragile uplands for continuous crop production in the humid and subhumid zones and to improve the traditional bush fallow slash-and-burn cultivation system. This led to research on the alley cropping system in detail (Kang et al. 1981, 1990), which became a precursor of several soil-fertility-improving agroforestry practices in tropics, including improved fallow system (Kwesiga et al. 2003), fertiliser tree system (Akinnifesi et al. 2008a, b, 2010; Sileshi et al. 2012) and evergreen agriculture (Garrity et al. 2010).

After more than three decades of research on alley cropping in various parts of the tropical and subtropical regions, better understanding has emerged about the potential and limitations of this technique, and areas requiring further research attention have been identified. The most encouraging results obtained so far have been from high base status soils. With proper husbandry and use of suitable hedgerow species, it is feasible to sustain yields of crops, such as maize, for some time with low fertiliser input. There is sufficient evidence to show the beneficial effects of alley cropping on soil fertility maintenance under high base status soils (Atta-Krah 1990; Kang and Ghuman 1991; Dagar 1995) and for controlling soil erosion to greater extent (Young 1989; Lal 1989; Dagar et al. 2014a, b). The magnitude of effects, however, varies with the hedgerow species used because this influences the quantity and quality of the prunings produced. Quality factors such as C/N ratio, lignin and, to a lesser extent, polyphenol contents determine the decomposition and nutrient release patterns of the prunings (Kang 1993). Lal (1989) and Kang and Ghuman (1991) showed that *Leucaena leucocephala*-based system maintained higher soil organic matter, extractable P and exchangeable cation status than the tilled treatment.

Several species such as *Leucaena leucocephala*, *Gliricidia sepium*, *Cajanus cajan*, *Desmanthus virgatus*, *Flemingia macrophylla*, *Inga edulis*, *Senna siamea*, *S. spectabilis*, *Calliandra calothyrsus*, *Alchornea cordifolia*, *Dactyladenia barteria*, *Sesbania grandiflora*, *S. sesban*, *Erythrina variegata*, *E. indica* and *E. poeppigiana* have been tested as hedgerow species in different parts of the tropics. There are great variations in the estimates of biomass yield and nitrogen fixation by different species. The nitrogen contribution of woody perennials, particularly leguminous species, is the most important source of nitrogen for agricultural crops in unfertilised alley cropping systems. Some data on biomass and nutrient yield (Table 3.5) by alley crops have been reported by Kang et al. (1989, 1990), Kang and Mulongoy (1992), Akinnifesi et al. (2010) and Sileshi et al. (2011, 2012) which prove *G. sepium* and *L. leucocephala* as ideal hedgerow woody perennials. Species such as *Alchornea cordifolia*, *Dactyladenia barteri*, *Gliricidia sepium*, *Leucaena leucocephala*, *Calliandra calothyrsus*, *Senna/Cassia siamea* and *Flemingia macrophylla* produced average pruned biomass of 3.77, 2.07, 5.18, 8.64, 6.13 and 21.3 Mg ha^{-1}, respectively, in an experiment conducted at the International Institute of Tropical

Table 3.5 Annual inputs of the major nutrient (kg ha^{-1}) from biomass[a] from fertiliser trees added to the soil

Tree species	N	P	K	Site (country)	Source[b]
Alchornea cordifolia	85	6	48	IITA, Ibadan (Nigeria)	Kang and Mulongoy (1992)
Cajanus cajan	82	–	–	Chikwaka (Zimbabwe)	Akinnifesi et al. (2010)
Calliandra calothyrsus	218	–	–	IITA (Nigeria)	Kang and Mulongoy (1992)
Dactyladenia barteri	41	4	20	IITA (Nigeria)	Kang and Mulongoy (1992)
Flemingia macrophylla	149	–	–	IITA (Nigeria)	Kang and Mulongoy (1992)
Gliricidia sepium	169	11	149	IITA (Nigeria)	Kang and Mulongoy (1992)
	33.7	2.0	21.4	Muheza (Tanzania)	Akinnifesi et al. (2010)
	67.3	–	–	Kalunga (Zambia)	Akinnifesi et al. (2010)
	72.1	–	–	Kagoro (Zambia)	Akinnifesi et al. (2010)
	74.4	5.2	42.5	Makoka (Malawi)	Akinnifesi et al. (2010)
	69.2	4.6	25.9	Msekera 2 (Zambia)	Akinnifesi et al. (2010)
	69.9	4.6	26.2	Msekera 1 (Zambia)	Akinnifesi et al. (2010)
Leucaena leucocephala	44.3	2.5	20.6	Mzekera (Zambia)	Sileshi et al. (2011)
	52.2	3.2	–	Machakos (Kenya)	Sileshi et al. (2011)
	57.5	3.5	27.4	Mzekera (Zambia)	Sileshi et al. (2011)
	74.6	4.7	29	Mzekera (Zambia)	Sileshi et al. (2011)
	75	4.0	22	Matomb (Cameroon)	Sileshi et al. (2011)
	200	10.0	–	Ibadan (Nigeria)	Sileshi et al. (2011)
	206	6.8	136	Ibadan (Nigeria)	Sileshi et al. (2011)
	247	2.0	184	Ibadan (Nigeria)	Sileshi et al. (2011)
	253	13.0	66	Calavi (Benin)	Sileshi et al. (2011)
	247	19	185	IITA (Nigeria)	Kang and Mulongoy (1992)
	301	19.3	156	Ibadan (Nigeria)	Sileshi et al. (2011)
	324	15.0	143	Ibadan (Nigeria)	Sileshi et al. (2011)
	343	17.0	211	Ibadan (Nigeria)	Sileshi et al. (2011)
	65.6	3.6	30.9	Msekera 1 (Zambia)	Akinnifesi et al. (2010)
Senna siamea	398	–	–	IITA Ibadan (Nigeria)	Kang and Mulongoy (1992)
Sesbania sesban	38	–	–	Chikwaka (Zimbabwe)	Akinnifesi et al. (2010)

[a]The prunned biomass of a plant added to soil
[b]Source: Adapted from Kang and Mulongoy (1992), Akinnifesi et al. (2010) and Sileshi et al. (2011)

Table 3.6 Amount of N fixed and derived from the atmosphere by some fertiliser trees in southern Africa

Species	N fixed (kg ha^{-1})	% Ndfa	Site (country)	References
Acacia angustissima	122	55–79	Chikwaka (Zimbabwe)	Chikowo et al. (2004)
	210		Chipata (Zambia)	Mafongoya et al. (2006)
Cajanus cajan (pigeon pea)	NA	65–84	Chikwaka (Zimbabwe	Chikowo et al. (2004)
	64	96–99	Nyambi (Malawi)	Adu-Gyamfi et al. (2007)
	85	94–97	Ntonda (Malawi)	Adu-Gyamfi et al. (2007)
	34	66–96	Gairo (Tanzania)	Adu-Gyamfi et al. (2007)
	54	95–99	Babati (Tanzania)	Adu-Gyamfi et al. (2007)
Gliricidia sepium	212	NA	Chipata (Zambia)	Mafongoya et al. (2006)
Leucaena collinsii	300	NA	Chipata (Zambia)	Mafongoya et al. (2006)
Sesbania sesban	84	55–84	Chikwaka (Zimbabwe)	Chikowo et al. (2004)
Tephrosia candida	280	NA	Chipata (Zambia)	Mafongoya et al. (2006)
Tephrosia vogelii	157	NA	Chipata (Zambia)	Mafongoya et al. (2006)

Source: Akinnifesi et al. (2010)
Ndfa nitrogen derived from atmosphere, *NA* not available

Agriculture (IITA), Ibadan, Nigeria. The nutrient contribution by these species ranged from 41 to 398 kg ha^{-1} year^{-1} N, 4 to 19 kg ha^{-1} year^{-1} P, 20 to 185 kg ha^{-1} year^{-1} K, 14 to 98 kg ha^{-1} year^{-1} Ca and 5 to 17 kg ha^{-1} year^{-1} magnesium (Kang and Mulongoy 1992).

Akinnifesi et al. (2010) stated that the legumes used in the sequential (e.g. fallow, relay) and simultaneous (e.g. intercrop) systems contribute to soil N through biological nitrogen fixation and capture of subsoil N (otherwise unutilised by crops). Estimates of the amounts of N accumulated by some fertiliser trees reviewed are given in Table 3.6. Out of the N accumulated, 55–84% is N derived from the atmosphere. Yield stability was determined for three long-term field trials (12–13 consecutive years) conducted at Makoka Research Station in southern Malawi and Msekera Research Station in eastern Zambia by Sileshi et al. (2012). At Makoka, the most stable yield was recorded in maize–*Gliricidia* intercrops. Average yield was highest for maize–*Gliricidia* intercropping amended with 50% of the recommended N and P fertiliser, and this was comparable with the yield recorded in monoculture maize that received inorganic fertiliser. On the two sites at Msekera, the highest yield was recorded in fertilised monoculture maize, followed by maize–*Gliricidia* intercrops. Yields were more stable, however, in maize–*Gliricidia* intercropping than fertilised maize on both sites at Msekera. It was concluded that maize yields remain more stable in maize–*Gliricidia* intercropping than in fertilised maize monoculture in the long term, although average yields may be higher with full fertilisation. Well-nodulated woody legumes such as species of *Sesbania* can fix 134–274 kg, sometimes even more, N ha^{-1} $year^{-1}$ in the field. This represents an average of 45% of their total N content. Thus, without taking into consideration differential partitioning of nitrogen fixed in the plant, when 10 Mg of prunings (3.5% N) are applied per hectare, there is an input of 160 kg N ha^{-1} from the atmosphere to the system.

This indicates that nitrogen-fixing woody perennials have considerable potential to supply N to the associated crops in the system. Besides soil improvement, studies conducted by Lal (1989) in Nigeria indicated that the soil erosion from *L. leucocephala*- and *G. sepium*-based plots was, respectively, 85 and 73% less than in the case of the plough-tilled control plots. *Leucaena leucocephala* contour hedgerows planted 2 m apart were as effective as non-tilled plots in controlling erosion and runoff. The infiltration rate was increased after 3 years of alleys, and bulk density decreased as compared to sole cropping. These studies also showed that, during dry season, the hedgerows acted as windbreaks and reduced the desiccating effects of 'harmattan' winds; soil moisture content at a 0–5 cm depth was generally higher near the hedgerows than in non-alley cropped plots. Limited results reported from the lowland semiarid zone have shown less potential for alley cropping as compared to the humid and subhumid zone (Kang 1993). However, the pruning of *G. sepium* (cut at 30 cm above ground) was incorporated in soil as manure during crop planting in Malawi, and the trees were managed to produce more green foliage, and the system acted as 'fertiliser factory' for over 15 years (Kwesiga et al. 2003). Thus, alley cropping system in addition to sustaining the yield of crops with low fertiliser inputs maintaining soil fertility and controlling soil erosion and weed control also provides various auxiliary products, such as fodder, staking material and fire wood.

3.2.6 Intercropping

Intercropping of fertiliser trees with cereal crops is an improvement building on the characteristics and advantages of alley cropping but minimising the biophysical limitations, such as 'hedge effect', competition and tree management (Akinnifesi et al. 2006, 2010). In intercropping, fertiliser trees are managed by means of periodic pruning. Pure stands of N-fixing species are normally planted in narrow spacing to allow planting of annual crops, and the fallows are left to grow for 2–3 years. At the end of the fallow period, the trees are cut, and the leaves and twigs are incorporated into the soil with a hand hoe. During the crop phase, the resprouting twigs are cut, and the coppice biomass (also called prunings) is incorporated into the soil. A cereal crop, usually maize, is planted between the tree stumps. It has been found that 33.7 to

Table 3.7 Annual inputs of the major nutrients (kg ha^{-1}) from biomass[a] of fertiliser trees added to the soil

Species	Tree management	Nutrient input			Site	References
		N	P	K		
Gliricidia sepium	Coppicing	33.7	2.0	21.4	Muheza (Tanzania)	Meliyo et al. (2007)
	Pollarding	71.9	4.4	45.8	Muheza (Tanzania)	Meliyo et al. (2007)
Leucaena leucocephala	Coppicing	65.6[b]	3.6	30.9[b]	Msekera 1 (Zambia)	Sileshi and Mafongoya (2006a)
	Coppicing	44.3[c]	2.5[c]	20.6[c]	Msekera 2 (Zambia)	Sileshi and Mafongoya (2006a)
Gliricidia sepium	Coppicing	69.9[b]	4.6[b]	26.2[b]	Msekera 1 (Zambia)	Sileshi and Mafongoya (2006a)
	Coppicing	69.2[c]	4.6[c]	25.9[c]	Msekera 2 (Zambia)	Sileshi and Mafongoya (2006a)
	Coppicing	72.1	–	–	Kagoro (Zambia)	Chirwa et al. (2003)
	Coppicing	67.3	–	–	Kalunga (Zambia)	Sileshi and Mafongoya (2006b)
	Coppicing	74.4	5.2	42.5	Makoka (Malawi)	Akinnifesi et al. (2006)
Sesbania sesban	Non-coppicing	38.0	–	–	Chikwaka (Zimbabwe)	Chikowo et al. (2004)
Cajanus cajan	Non-coppicing	82.0	–	–	Chikwaka (Zimbabwe)	Chikowo et al. (2004)
Gliricidia sepium	Coppicing	–	2.2	13.2	Msekera (Zambia)	Sileshi and Mafongoya (2006b)
	Coppicing	–	4.3	25.3	Kalunga (Zambia)	Sileshi and Mafongoya (2006b)

Source: Akinnifesi et al. (2010)
Msekera 1 and 2 represent experiments during 1992–1993 and 1997–2003, respectively
[a]In the case of coppicing species, this represents only coppice biomass, while in non-coppicing, both litter and standing leaf biomass are considered
[b]Average of 9 years
[c]Average of 5 years

82 kg of nitrogen, 2.0 to 5.2 kg of phosphorus and 13.2 to 45.8 kg ha^{-1} of potassium is added annually into the soil by different fertiliser species (Table 3.7).

The best-known example is the *Gliricidia*–maize intercropping in Malawi and Zambia (see Chaps. 8 and 9 by Sileshi et al. in this volume). For instance, in a long-term trial at Makoka in Malawi, Akinnifesi et al. (2006) showed that *Gliricidia*

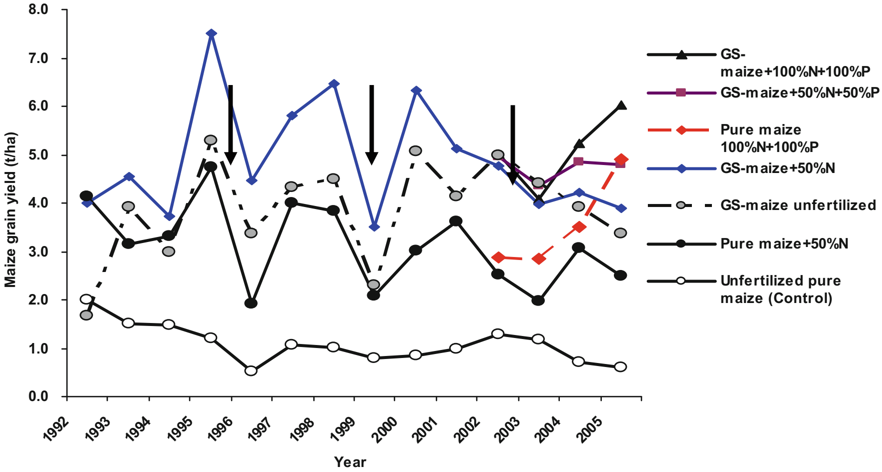

Fig. 3.1 Long-term maize grain yield as affected by fertiliser and pruning incorporations in a *Gliricidia sepium*–maize intercropping at Makoka, Malawi. Arrows indicate flood due to excessive rainfall in 1996/1997 and droughts in 1999/2000 and 2003/2004 seasons. *Gs Gliricidia sepium*, *N* nitrogen, *P* phosphorus (Source: Akinnifesi et al. 2010)

intercropping with maize increased maize yield in the ranged of 100 to 500%, averaging 315% over a 10-year period. Increase in yield is more evident in the 3rd year after tree establishment and onwards. The unfertilised plots not amended with *G. sepium* had steadily declined yield, and amendment with N and P could not sustain high maize yield over time (Fig. 3.1). Continuously cropped maize plot without *G. sepium* or fertiliser declined steadily from 2 Mg ha^{-1} at the start of experiment in 1992 to half a Mg in 2006. Unfertilised maize under *G. sepium* maintained yield at 3–4 Mg ha^{-1}. When the intercrop plots were amended with 46 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1} (representing 50% N and 100% P, respectively), there was a 79% increase in grain yield over the recommended practice, indicating complementarity between applied fertiliser and organic inputs from *G. sepium* (Akinnifesi et al. 2007). The result agreed with a comprehensive meta-analysis on 94 peer-reviewed publications across SSA, reaffirming the superior performance of N-fixing fertiliser tree legumes (Sileshi et al. 2008a, b). The work compared published data over two decades involving more than 15 countries, 200 partner agencies and 50 multidisciplinary scientists working in discretely or loosely connected modes.

Soil biological processes (mediated by roots, microbial flora and fauna) are an integral part of the functioning of natural and managed ecosystems, and the soil biota is considered to be potential indicator of soil health and sustainability of the system. Soil microflora such as fungi and bacteria are responsible for the breakdown of plant litter and thin roots in the soil and the nutrients essential for the plants getting released. Fertiliser trees increase the biological activities in soil and also help in making nutrients available to the associated plants/crops. However, only few studies have examined the effect of fertiliser trees on soil biological properties. In one study conducted in Zimbabwe (Mafongoya et al. 1997) using leaf biomass of various fertiliser trees, microbial biomass carbon and nitrogen were not found differing among treatments. However, fungal actinomycete populations differed with the biomass of legume species used as well as the method of biomass application.

Among the macrofauna essential in soil processes in agroecosystems, probably the most important ones are the so-called ecosystem engineers (termites, earthworms and some ants) and the litter transformers including millipedes, some beetles and many other soil-dwelling invertebrates. 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. These have been used to monitor changes in soil quality and to provide early warning of adverse trends and to identify problem areas. In five separate experiments conducted in eastern Zambia, the number of invertebrate orders per sample and the total macrofauna (all individuals per square metre) recorded were higher when maize was grown in association with tree legumes than under fertilised monoculture maize. Similarly, densities of earthworm and millipede were also higher than under monoculture maize (Sileshi and Mafongoya 2006a, b). Cumulative litter fall, tree leaf biomass and resprouted biomass under legume species appeared to explain the variation in macrofaunal densities (Sileshi and Mafongoya 2007). Litter transformer populations were found to be higher under *Gliricidia*, which produced good-quality organic inputs, than among the other fallow species. On the other hand, a higher population of ecosystem engineers was found under trees that produce poor-quality organic inputs (Sileshi and Mafongoya 2006a, b).

3.2.7 Homegardens

Tropical homegardens depict a transition stage between tropical forest ecosystem and arable cropping that mutually supports the sustainable agriculture and forest ecosystems. Tropical homegardens consist of an assemblage of plants, which may include trees, shrubs, palms, vines and herbaceous plants growing in or adjacent to a homestead or home compound. These are intended primarily for household consumption, and there is intimate association of woody perennials with annual and perennial crops and invariably livestock within the compounds of individual houses, with the whole crop–tree–animal unit being managed by family/labour. These are rich in biodiversity. Nair (1993) mentioned the local names to homegardens found in Africa. These include 'compound farms' in humid lowlands of southeastern Nigeria (rainfall 2000–4000 mm, mean management units 0.5 ha), 'Chagga homegardens' in highlands of north Tanzania (rainfall 1000–1700 mm, mean management units 0.68 ha) and '*Ka*/*Fuyo* gardens' in semi-arid to subhumid regions of Burkina Faso (rainfall 700–900 mm, mean management units 0.5 ha). Most important function of homegardens is food production for daily need. However, there are several secondary outputs also. In some compound farms, out of 64 woody species, 62 were reported to be food producing.

Okafor and Fernandes (1987) reported 69 multipurpose wood species found in compound farms of southeastern Nigeria. These included bearing useful fruit, vegetables, oil, fodder, wood of commerce, fuelwood, fencing and thatching material, condiments and medicinal woody perennials. They also conducted an analysis of the edible parts (fruit, seeds and nuts) of some trees in these compound farms and reported that most of them contained substantial quantities of fat and protein. Seeds of *Irvingia gabonensis*, nuts of *Tetracarpidium conophorum* and the fruit pulp of *Dacryodes edulis* are rich in fat (44–72%), whereas nuts of *T. conophorum* and *Pentaclethra macrophylla* contain high quantities of protein (15–47%).

In *Chagga* homegardens, out of 53 woody species, 13 were found to be food producing, while in *Ka/Fuyo*, out of 7, there were 5 food-producing species. In these homegardens, reported herbaceous species were 73, 58 and 7, respectively. In southern Nigeria, yam, cocoyam and banana are main food crops, while kola (*Cola* spp.) and oil palm are cash crops. Goats, sheep and poultry are main animal constituents. In *Chagga* homegardens, banana, beans, *Colocasia*, yams and *Xanthosoma* are main food crops and coffee and cardamom the cash crops. Cattle, goats, pigs and poultry for meat are main animal constituents. The *Chagga* in the foothills of Mountain Kilimanjaro, the Matengo Ngoro-Pit system in highlands of Mbinga District and Ngitill system in western Tanzania are homegarden systems of Tanzania, and compound farms of West Africa growing multipurpose trees, fruits and food crops (yams, plantain, maize, etc.) along with animals are still popular (Boffa 1999; Nair et al. 2016). In the Chagga system, tall trees such as *Cordia abyssinica*, *Diospyros mespiliformis* and species of *Albizia* form upper storey; banana and coffee come in second storey; and food crops, fodder, cardamom, and medicinal herbs come in lower storey. In this system, there is high degree of nutrient cycling, and permanent cover on soil helps in conserving soil as well as moisture. These systems are valuable gene pool. There is plenty scope of introduction of improved apiculture practices and nitrogen-fixing trees in the system (Kitalyi et al. 2013). In *Ka/Fuyo* gardens, maize and red sorghum are main food crops, tobacco cash crop, and goats, sheep and poultry the animal constituents. The farm families supplement the nutrition in their diet from these products.

In Namibia, most of the households retain indigenous fruit trees such has marula (*Sclerocarya birrea*), jackal berry (*Diospyros mespiliformis*), manketti (*Schinziophyton rautanenii*), makalani palm (*Hyphaene petersiana*) and monkey orange (*Strychnos cocculoides*) near their households (Dagar 2003). Most of these are very rich in vitamin C, mineral and protein contents, and are part of famine food for the rural people. In an attempt to domesticate and improve indigenous fruit trees in southern Africa, Mateke (2000) reported the nutritional composition of selected fruit trees. The chemical and nutrient composition of some fruits compiled from different sources (Arnold et al. 1985; Wehmeyer 1986; Saka and Msonthi 1994; Keya et al. 2000; Akinnifesi et al. 2008c) has shown that many of these are rich in these contents. Most of the data generated in these systems are commodity based. A system approach should provide the basis for research on homegardens, and the studies must include both biological and socio-economic aspects. Changing species composition by introduction of new or improved tree or crop species, intensified cropping patterns (including multi-tiered system), inoculation of beneficial microorganisms such as VAM fungi and vermiculture, nutrition management and interaction of cattle or poultry are primary areas of improvement of these systems.

3.2.8 Trees Dispersed on Croplands (Parkland Systems)

Trees with multipurpose uses are often intentionally planted in crop fields or allowed to persist from natural regeneration or retained while clearing the natural forests for agricultural purposes. Wide range of tree species is often grown with staple food crops in random spacing. Although no definitive estimate exists, the parkland system, characterised by mature trees widely dispersed in cropped fields, is the largest single agricultural land use in SSA. Some parklands are monospecific (e.g. *Faidherbia albida* and *Borassus aethiopum*-based), but others have dominant tree species mixed with a range of tree and shrub species (Boyala et al. 2014). In some instances, the original species such as *Prosopis africana*, *Vitellaria paradoxa*, *F. albida* and *Parkia biglobosa* are retained, while in some other cases, cash plantations such as oil palm (*Elaeis guineensis*) are introduced, while in others (e.g. *Adansonia digitata*), even fruits and leaves are collected systematically, and these are improved as compared to traditional ones. So is true with *Acacia senegal* and *A. laeta* parklands of Sudan, where gum is collected from these trees and *F. albida* is intercropped successfully with maize. A view of parklands in Sahel is shown in Fig. 3.2.

Fig. 3.2 A view of the 'parklands' (scattered mature trees) in Sahel in Sub-Saharan Africa (Photo credit to Chris Reij)

Across the entire Sudano-Sahelian zone of West Africa, one finds crops planted under varying densities of mature trees. The ability of these parklands, or two-tiered systems, to enhance and stabilise crop production has been much studied over the past 30 years in West Africa. Kessler (1992) reported that approximately 20 different tree species are common in these parklands. Scientific studies on the interaction between such trees and the intercropped agricultural crops have been few and limited to a few tree species such as *Faidherbia* (*Acacia*) *albida* in West Africa (Vandenbeldt 1992). The crop yields under the trees are generally reported to be higher than in the open field. Kho et al. (2001) separating the effects of trees on crops in Niger found that millet production under *F. albida* canopy was about 36% higher than in open field. The nitrogen and phosphorus availability was, respectively, 200% and 30% higher than the open causing increase in production by 26% and 13%, respectively. The net effect via other resources was negligible. However, Kessler (1992) and Karter et al. (1992) studied the negative influence of *Vitellaria paradoxa* (shea butter/*karite*) and *Parkia biglobosa* (*nere*) in Burkina Faso and Mali. In both cases, sorghum grain yields were reduced by 50–70%, due to reduced light availability under the trees. The pruning of tree branches may be management option to reduce the magnitude of yield reduction. In Namibia, Chikasa et al. (2002) reported 76% increase in grain yield of pearl millet when grown with *Acacia nilotica* (pollarded), and highest stover yield of 161% was obtained from pearl millet grown with C*olophospermum mopane*.

3.2.9 Fodder Banks and Silvopastoral Systems

These are land use systems in which woody perennials are combined with livestock and pasture production on the same unit of land. Cut-and-carry (protein bank), live fence posts and fodder foliage and browsing and grazing are main components of these practices. Silvopastoral systems involving a large number of trub species and various management intensities, ranging from extensive nomadic silvopastoralism to very high intensity and improved cut-and-carry fodder systems, have been described at various sites. Livestock forms a major component of agricultural productivity in many developing countries of Africa. For example, livestock makes up to 30–40% (80% in Mauritania) of the agricultural gross domestic production in the Sudano-Sahelian countries of West Africa (Nair 1993) where most of the cattle population are raised primarily for food products. Basically, two types of silvopastoral systems exist in the semiarid tropics: those with a crop component and those without. In the Sahel, grazing on natural grass- and shrublands predominates in the northern arid regions and postharvest grazing on agricultural residues in parklands in southern zones with annual rainfall exceeding 350 mm. 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.

Throughout the semiarid tropics, animals are grazed on harvested fields. In dry season, they derive between 50 and 80% of their feed intake from crop residues

(Sanford 1987). In Botswana, Shorrock (1981) estimated that 25% of the total annual diet of livestock was composed of browse trees and shrubs. Le Houerou (1980, 1992) listed nutritional qualities of some tree and shrub fodders. Crude protein ranged from 12.3% in *Balanites aegyptiaca*, 14.7% in *Acacia albida*, 16.2% in *Combretum aculeatum*, 16.5% in *A. raddiana* and 21.4% in *Boscia angustifolia* to 22.5% in *Maerua crassifolia*. The chemical composition in the leaves of some trees (mostly legumes) being grown in Africa shows that many of them are rich in protein and other contents (Table 3.8).

Dulormne et al. (2003) assessed nitrogen fixation dynamics in a cut-and-carry silvopastoral system. Dinitrogen fixation ranged from 60 to 90% of the total N in aboveground tree (*Gliricidia sepium*) biomass depending on season. On an average, 76% of N exports in tree pruning (194 kg N ha^{-1} $year^{-1}$) originated from N_2 fixation. Grass production averaged 13 Mg ha^{-1} $year^{-1}$, and N export in cut grass was 195 kg N ha^{-1} $year^{-1}$. The total N fixation by *G. sepium* as estimated from the tree and grass N exports and increase of soil N content was 555 kg N ha^{-1} $year^{-1}$. Carbon sequestration averaged 1.9 Mg C ha^{-1} $year^{-1}$, and soil organic N in the 0–0.2 m layer increased at the rate of 166 kg N ha^{-1} $year^{-1}$, corresponding to 30% of nitrogen fixation by the tree.

Livestock pressure must be balanced as per carrying capacity of a rangeland. However, most grazing lands in semiarid Africa are communally exploited. *Faidherbia albida* is an important tree of the scattered tree or parkland systems in the Sahel. As discussed earlier, it helps in increasing productivity of croplands as well as pastures. Similarly, *Acacia tortilis*—grassland system in East Africa—has helped in improving soil fertility of grazing lands. Belsky (1994) concluded that nutrient (notably nitrogen) is a major limiting factor and that the fertility effect is most likely an important part of overall tree effect. Roothaert and Franzel (2001) reported that improved, stall-fed dairy animals were the dominate livestock type in the subhumid zone whereas communally grazed, local-breed cattle and goats in dry zone. A total of 160 local fodder trees and shrubs used by farmers have been reported. The most frequent criteria were the contribution towards animal health, palatability and drought resistance. Belsky et al. (1993) while studying the effects of widely spaced trees of *Acacia tortilis* and *Adansonia digitata* and livestock grazing on understorey environments in tropical savannas of Kenya reported that tree-crown zones at lightly and moderately grazed sites had a unique understory flora and higher plant biomass, lower temperatures and bulk density and higher levels of P, K, Ca and mineralisable N than their associated grassland zones. In the heavily grazed savanna, only few differences were found in these parameters. The beneficial effects of savanna trees on their understorey environments appear to diminish with increasing livestock utilisation.

Table 3.8 Chemical composition and nutrient contents (% DM basis) in leaves of some fodder trees and shrubs grown in tropical Africa

Species	Dry matter %	Crude protein	Neutral detergent fibre	Acid detergent fibre	Crude fibre	Lignin	Dry matter digestibility (in vitro)	N	P	K	Ca
Acacia nilotica	85.0	13.6	31.6	22.5	–	5.3	–	–	–	–	–
A. tortilis	89.4	13.0	32.4	24.2	–	4.8	–	–	–	–	–
Albizia lebbeck	–	22.1	44.2	–	–	–	–	–	–	–	–
Alchornea cordifolia	–	–	–	–	–	–	–	3.29	0.23	1.74	0.46
Azadirachta indica	36.0	15.0	–	–	13.8	–	–	–	–	–	–
Cajanus cajan	90.0	21.7	–	–	30.2	–	–	3.60	0.20	–	–
Senna siamea	–	12.4	45.6	43.5	–	25.3	–	2.52	0.27	1.35	–
Dactyladenia barteri	–	–	–	–	–	–	–	2.57	0.16	1.78	0.90
Erythrina poeppigiana	–	32.0	–	–	–	–	44.0	3.30	0.18	1.16	1.52
Faidherbia albida	88.0	14.3	37.4	27.9	–	4.5	–	–	–	–	–
Gliricidia sepium	19.9	27.6	36.1	27.8	5.3	2.1	61.5	4.21	0.29	3.43	1.40
Inga edulis	–	–	–	–	–	–		3.1	0.20	0.90	0.70
Leucaena leucocephala	69.0	22.0	–	–	18.3	–	–	4.33	0.28	2.50	1.49
Sesbania sesban	–	26.4	38.7	–	–	–	–	–	–	–	–

Source: Nair (1993)

3.2.10 Woodlots and Other Agroforestry Trees for Fuelwood Production

The developing world is facing a critical firewood shortage as serious as the petroleum crisis. Eckholm (1975) estimated (in early to mid-1970s) that no less than 1.5 billion people in developing countries derive at least 90% of their energy requirements from wood and charcoal and another billion people meet at least 50% of their energy needs this way. Since then, the situation in many countries has not changed much, and fuelwood use is certainly a contributory element to the degradation of land resources in agricultural regions where resource pressures are more. The results of tree planting projects for fuelwood production, however, have generally not been encouraging. The basic reason for this situation is that the small farmers' preference is always for trees that yield multiple outputs, and partially, it is because of the gender issue that is involved as men may not consider firewood shortage as a serious problem, but women do. Great potential exists for enhancing fuelwood production through agroforestry and social forestry programmes. In order to make such initiatives a success, fuelwood should be promoted as a subsidiary benefit rather than the prime end product, and the species selected should be locally adapted and accepted income-generating trees that yield multiple products. Akinnifesi et al. (2010) and Sileshi et al. (2014) have given detailed account regarding utilisation of several multipurpose trees as woodlots and in agroforestry systems in different regions of Africa.

3.3 Services Provided by Agroforestry Systems

The types of agroforestry systems are complex and diverse, and they are virtually innumerable. Nair et al. (2016) have reported a qualitative SWOT (strengths–weaknesses–opportunities–threats) analysis of the selected indigenous agroforestry systems showing several commonalities among them. While sustainability, multifunctionality and high sociocultural values are the common strengths, low levels of production and lack of systematic research and technological inputs to improve the systems are the major weaknesses. The opportunities emanating from strengths and weaknesses are also common to most of the systems, and threats to these systems arise mostly from ramifications of government policies. Besides the agroforestry systems/practices discussed earlier, some practices such as fuelwood lots, fodder banks, scattered multipurpose or fruit trees on farmlands/pastures, boundary plantation, live fences, tree planting for reclamation and improvement of problem soils, trees for windbreaks/shelterbelts, sand dune stabilisation and soil conservation and establishment of woody and herbaceous vegetation for rehabilitation of mine spoils are important. Some of these are discussed in brief in the following sections:

3.3.1 Agroforestry for Soil Conservation and Amelioration

Soil erosion has, in all livelihood, been a problem since time immemorial, but the soil conservation efforts were taken more seriously after formulation of the World Soil Charter by FAO (1982) and increased global emphasis on environmental issues and combating desertification. Today, soil conservation encompasses both soil-erosion control and maintenance of soil fertility. On highland situations, alley cropping has been undoubtedly proved a successful technique for soil conservation, sustainable production and maintaining soil fertility. Throughout the African continent, farmers use windbreaks to protect crops, water sources, soil and settlements on plains and gently rolling farmlands. Hedgerows of *Euphorbia tirucalli* are found grown very commonly to protect maize fields and settlements in dry savannas of Tanzania and Kenya. Tall rows of *Casuarina* may be seen along the canals and irrigated fields in Egypt, and multispecies shelterbelts are found grown in Chad and Niger for controlling the spread of deserts on croplands. Small live fences and hedgerows can also act as windbreaks for small sites such as homegardens and nurseries. The most effective windbreaks provide a semipermeable barrier to wind over their full height from the ground to the crowns of the tallest trees. An ideal windbreak should consist of a central core of a double-row planting of fast and tall growing species such as *Eucalyptus, Casuarina* or neem (*Azadirachta indica*) and two rows each of shorter spreading species such as species of *Cassia*, *Prosopis*, *Gliricidia* or *Leucaena* on both sides of central core. Species of *Agave* and *Euphorbia* are also used, especially on the outer rows, away from crop fields.

Diversifying the species in the windbreaks can also bring a wider variety of useful products to local users. Selection of species should be based on the compatibility, environmental hazards (such as insects and pests), palatability to wild and domestic animals, soil conditions, water management, microcatchments, etc. The widely mentioned study of windbreaks in the Sahel is that by CARE in the Majjia Valley in Central Niger where over 350 km of windbreaks protect 3000 ha of millet and sorghum fields by growing neem tree. When the wind breaks were 10 years old, the yields of millet from the protected area were 23% greater than the unprotected millet on a gross area basis (Vandenbeldt 1990). Lal (1989), Young (1989), Nair (1993) and Dagar and Singh (2018) have given detailed accounts on the role of agroforestry in soil conservation in various ecoregions. Soil amelioration by fertiliser trees dealt in earlier sections is equally relevant here.

3.3.2 Sociocultural and Recreational Value

The indigenous and traditional systems have been appreciated for ecological principles and sustainability, but very little attention has been paid towards the recreational and cultural values of the agroforestry systems. Some of the systems, for example, cultivation of ornamental fish and presence of coral reefs in association with mangroves, are the most attractive features in many coastal regions of the world. Many sacred groves are another socioreligious site in many localities across the globe. Many tribal people collect traditional forest non-timber produces such as leaves (making traditional plates, cups, etc.), medicinal drugs, honey and gum of commerce, from woodlots for their livelihood security without damaging the ecology. The aborigines also use fruits as food; ooze a fluid used as toddy or neera; and make jaggery from fruit juice and leaves are used for making brooms, baskets, fans, floor mats, etc. Thus, there are many unrecorded cultural tales associated with traditional agroforestry systems which need documentation. Urban and peri-urban forestry is another attraction in recent years.

3.4 Enhancing Livelihood and Nutritional Security

African countries face a worsening crisis in the availability of food for the fast-growing population resulting to poverty, food shortage, malnutrition and health problems. Periodic drought aggravates the situation, but even in years of favourable rainfall, most farm families cannot produce enough food to feed themselves. Due to frequent burning of forests, the indigenous fruit and other multipurpose trees are rapidly disappearing. Agriculture is still the main source of livelihood for more than three-fourth of the rural population. Agricultural production is currently constrained by unaffordable inputs (especially fertilisers), lack of irrigation facilities, lack of access to credit and minimum involvement of smallholders in the market economy and agricultural policies. The root cause of low per capita food production is soil fertility depletion. Smalling et al. (1997) reported that soils in Sub-Saharan Africa are being depleted at annual rates of 22 kg ha^{-1} for N, 2.5 kg ha^{-1} for P and 15 kg ha^{-1} for K. Sanchez et al. (1997) recommended a two-pronged strategy to stop the nutrient mining through replenishing phosphorus and nitrogen. About 530 million ha African soils are high phosphorus fixing which is now considered an asset rather than liability. Application of inorganic phosphorus fertilisers is necessary to overcome the depletion of this element (Jama et al. 1997). One-time application of phosphate rock can be helpful to desorb acids created by the decomposition of organic inputs like *Tithonia diversifolia* which produce organic acids to help acidify the phosphate rock. The organic sources like animal manure and compost, biomass transfer and efficient use of trees and shrubs may help in nitrogen replenishment, and their deep roots help in mining the minerals from subsoil depths beyond the reach of crop roots and transfer them to the top soil via decomposition of litter. By strategic planting of trees, nitrogen lost over the years can be replenished with nitrogen from agroforestry innovations such as hedgerow intercropping with *Leucaena* or *Gliricidia*, biomass transfer along with *Tithonia*, application of manure with foliage of *Calliandra calothyrsus,* and through improved fallow systems using nitrogen-fixing shrubs like *Sesbania sesban*, *Tephrosia vogelii*, *Cajanus cajan* and *Gliricidia sepium* as discussed earlier.

Thus, low-cost technologies and easily adaptable practices are needed for smallholders to sustain the productivity of their crop fields, pastures (including of livestock) and forest products. Agroforestry provides such options. The contribution of forest products (besides commercial timber) such as indigenous fruits and their products, medicine and thatching material to the rural household economies could be significantly high. Besides the importance of their nutritional value in balancing the diet of poor community people, many fruit tree species may be commercially exploited for better economic gains of their products such as juice, beverages, jam, jelly and alcoholic drinks. This requires strengthening of the domestication programmes of indigenous fruit trees which are plenty in natural forests and may be blended in various agroforestry systems. This will not only help in restoring the forest wealth (which otherwise is being deteriorated) for present and future generation but also help in providing food and nutritional security to poor people and conserving soil and environment. This aspect has been discussed in brief here.

3.4.1 Status of Indigenous Fruit Tree Species (IFTS) of Tropical Africa

The tropical subregions of the continent are diverse in their climate, soil, topography and vegetation and home to many valuable fruit and nut tree species, whose potential have not fully realised. Many of these are of local importance and have not yet domesticated though their economic produces are harvested from their wild stands or grown as volunteer stands in homegardens, farmlands and forest reserves (Dagar 2003; Meregini 2005). At least 477 edible fruit and nut species (including some exotics) are grown across the landscape of Africa (Bosch et al. 2002; Siemonsma et al. 2004) out of which some scanty researched local species have been identified and listed by Awodoyin et al. (2015). Based on the perusal of literature (mainly Palgrave 1983), extensive surveys and confirmation with other persons of various walks particularly Directorate of Forestry during visits to central and north-eastern regions of Namibia, Dagar (2003) listed 66 IFTS to be preferred among various communities living in the forest areas of Namibia for traditional uses of course mainly as fruits. Most of these are also common in countries of southern Africa. Many of these also have ethnomedicinal values and are used by local people in various ways. Species such as marula (*Sclerocarya birrea*), monkey oranges (species of *Strychnos*) and manketti (*Ricinodendron rautanenii*) have already been identified as potential and commercial species for domestication.

Despite of availability of local fruit and nut species, the fruit production in Africa is predominated by introduced species mainly from tropical Americas and Asia (NAP 2008). These include bananas (*Musa* spp.), *Citrus* spp., mango (*Mangifera indica*), papaya (*Carica papaya*), pineapple (*Ananas comosus*), pomegranate (*Punica granatum*), avocado pear (*Persea americana*), cashew (*Anacardium occidentale*), coconut (*Cocos nucifera*), carambola (*Averrhoa carambola*), custard apple (*Annona squamosa*), date palm (*Phoenix dactylifera*), guava (*Psidium guajava*), grapevine (*Vitis vinifera*), passion fruit (*Passiflora edulis*), jackfruit (*Artocarpus heterophyllus*), hog plum (*Spondias mombin*) and mulberry (*Morus alba*). These are commonly preferred because of availability of know-how of these species. Most African indigenous species have not been brought up to their full potential in terms of quality, breeding and selection, scale of production and distribution, value addition and availability. In terms of geographical spread except a few, these have not crossed African shores as compared to tropical fruits of other continents. There is urgent need of identification, evaluation, development of cultivation technologies, value addition and marketing of selected potential IFTS. A number of studies laid the foundations for domestication, by clarifying the role of fruit trees for rural livelihoods (Leakey and Simons 1998; Schreckenberg et al. 2006; Faye et al. 2010, 2011; Leakey et al. 2012) and setting priorities for domestication (Franzel et al. 2008). During the last four decades, attempts have been made to develop techniques for vegetative propagation (Sanou et al. 2004; Verheij 2004; Hartmann et al. 2007), management of genetic resources (Rao and Sthapit 2012; Ahuja and Ramawat 2014) and genetic improvement through establishment of provenance trials and using molecular markers (Sina 2006; Diallo et al. 2007). Some important examples have been mentioned later in this chapter showing the attention being paid to domesticate IFTS in tropical Africa and to bring them at the global market.

3.4.2 Domestication of Indigenous Fruit Trees

Tree domestication has been explained by many workers in their own way in the fields of agroforestry, agronomy, agroecology and plant breeding (Pauku 2005; Akinnifesi et al. 2008c). The World Agroforestry Centre (ICRAF) defines domestication as the socio-economic and biophysical processes involved in the identification, characterisation, selection, multiplication and cultivation of high-value tree species in managed systems (Garrity 2008). However, in more simple way, domestication is a process of naturalising or settling a species (whether plant or animal) from natural habitat as a member of household. In present context, cultivation of tree species growing naturally (in the wild) on farm or in homegardens for their anthropogenic change in the genetics to conform to human needs and agroecosystem (Awodoyin et al. 2015). Therefore, domestication of indigenous fruit tree species is a procedure involving the extent, identification, production, management and adoption of desirable germplasm. Strategies for individual species vary according to its extent in nature, functional use, profitability and biological and ecological adaptations in the targeted environment. Domestication of IFTS must aim at economic potential as a cash crop, fruit as such or its products, meeting the food and nutritional requirements of grower, and to provide incentive to subsistence farmers to grow such trees contributing towards poverty reduction.

The domestication of Kiwi (*Actinidia chinensis*) and mango (*Mangifera indica*) are classical examples of new horticultural fruits of international significance. Kiwi was first grown commercially in New Zealand in the 1930s, despite its more than 1000 years of history in China. Mango, with its many cultivars, was brought from different parts of the world and domesticated in the Sahel (Rey et al. 2004). The selection of the macadamia nut (*Macadamia integrifolia*) from Australia also began in 1934, motivated by promising market interests. Their wide adaptation across the globe is now history. These successes were achieved by farmer-led domestication and commercialisation efforts. The domestication of many other trees of the tropics was triggered by globalisation, especially during the colonial conquests, followed by growing market demands that promoted the research and cultivation, and propagation technologies were developed. Compared to this, local fruit tree species have only undergone intentional selection to a limited degree, and most of them must be underexplored or semi-domesticated in the genetic sense of the word. Selection in favour of superior trees by farmers may slowly have improved the productivity of the species (e.g. *Sclerocarya birrea* and *Vitellaria paradoxa*) but not to the extent that differences between improved and unimproved trees are easily observed (Raebild et al. 2011). However, a number of projects dealing with formal domestication of mainly indigenous species have recently been undertaken, and deliberate tree improvement programme involving specific interventions for useful characters has been advocated for some highly promising IFTS of West African Sahel and sub-Saharan regions (Kwesiga et al. 2000; Dagar 2003; Akinnifesi et al. 2004, 2008c; Raebild et al. 2011; Awodoyin et al. 2015). The extent of sufficient local resources, their detailed ecological and biological studies, proper identification and selection procedures, propagation technologies, value addition and proper marketing facilities and farmer-oriented policies are necessary for the success of domestication programmes. Some efforts have already been made and shown the path for success of such programmes. A brief account of some such attempts made is given here in the following text.

3.4.2.1 Extent of Resources

As mentioned earlier, it is very important to have the knowledge of the extent of available resources in the form of natural stands, i.e. vegetation. For that, we must study the ecology of the natural vegetation and ethnobiology and preserve the available biodiversity. For example, Mendelsohn et al. (2000) and Mendelsohn and El Obeid (2003) gave a detailed account of vegetation in north-central and the Kavango Region of Namibia where 35 vegetation types on an area of 84,608 km^2 are found out of which 849,901 ha area is fenced or cleared. The Kavango Region has been classified into 11 vegetation types. In many of these areas, there are the remains of old dunes, and the vegetation varies considerably between that on the sandy dunes and the more clayey soils in the inter-dune valleys. Thus, tall teak (*Pericopsis elata*), false mopane/*msivi* (*Guibourtia coleosperma*), *Burkea* (*Burkea africana*), kiaat/*mukwe* (*Pterocarpus angolensis*) and mangetti (*Schinziophyton/Ricinodendron rautanenii*) trees often dominate the deeper sands, while low-lying, more clayey soils are characterised by shrubby vegetation and patches of grasslands. *Diospyros* also prefers clayey soil. Most of these stands are rich in IFTS, which are used by the community people in many ways in their routine life. Nuts and fruits from between 35 and 50 different species are consumed in any one area. Most of these are taken only occasionally, but some, especially mangetti, marula, monkey oranges and *msivi*, provide relatively large quantities of food. Many IFTS also possess medicinal properties. But, unfortunately, most of the stands are burnt year after year, especially so in eastern Kavango and the Caprivi Strip. The average area burnt over 13 years (from 1989 to 2001) was reported to be 32% (Mendelsohn and El Obeid 2003). In this process, many fruit trees and their saplings are killed, and as a result in many stands, the tree population of many IFTS is becoming thin. With the exception of manketti, the availability of indigenous fruit species has decreased in the last 3 decades. *Guibourtia coleosperma* is frequently cut as it is a preferred wood species for woodcarvers, and people also use it for fencing and construction. Fruit trees that do not fruit (anymore) are often seen as useless and cut down for firewood or other purposes. It was furthermore informed that people even cut down indigenous fruit trees if they want to harvest but cannot reach the fruits. Small trees are not really cared for.

In the forests of north-central region, marula (*Sclerocarya birrea*), manketti (*Schinziophyton rautanenii*), *Berchemia discolor*, monkey oranges (*Strychnos cocculoides*, *S. pungens*) and *Diospyros mespiliformis* are prominent fruit trees. In the Caprivi region of Namibia, *Berchemia discolor*, *ibbu* (*Vangueria infausta*), *baobab* (*Adansonia digitata*), *Parinari curatellifolia*, *Ximenia* spp. and *Grewia* spp. are predominant in natural stands. These fruits are already consumed, stored and transformed in various products by the rural people. While commercialising a fruit product, it must be ensured that the particular fruit tree is planted (domesticated) in large area so that the same is not exploited in its natural habitats. This, in turn will also take care of environmental aspects. In southern Africa, *Uapaca kirkiana*, *Parinari curatellifolia*, *S. cocculoides* and *S. birrea* are in abundance and collected from the wild and consumed.

3.4.2.2 Traditional Uses

For a long time, indigenous fruit trees have been recognised as important species by farmers with smallholding, who have from time immemorial used their fruits to supplement their diets and income through selling to urban markets. Efforts in the past have largely been devoted to documentation of their utilisation at household level, traditional conservation practices of protecting the valued indigenous fruit trees, the informal marketing in southern African countries and ethnomedicinal uses. Most of the fruits are available mainly during the rainy season when crops are not ready for harvest and hence contribute significantly to the diets of the rural people. Besides fruits, some of the plants are used for food in the form of leaves, pods, seeds and roots. Dried fruits or kernels of some plants serve as porridge. Many serve as refreshing beverages or kind of liquor. Many fruits besides being consumed locally are also sold in local and roadside markets. Traditional fruits such as marula (*Sclerocarya birrea*), monkey orange (*Strychnos* spp.), bird plum (*Berchemia discolor*), *Diospyros* spp., *Grewia* spp. and manketti (*Schinziophyton rautanenii*) have become part and parcel of the life of rural masses. They use most of these IFTS in more than one way. Based on available literature including on ethnobotany (Palgrave 1983; Kwesiga and Kamau 1989; Maghembe and Seyani 1992; Maghembe et al. 1998; Tchoundjeu et al. 2008; Raebild et al. 2011) and the survey in FAO Project (Dagar 2003), the traditional uses of IFTS may be summarised under the following categories (there will certainly be a wider range of uses and species in different regions):

1. **Edible fruits consumed as dessert**: Ripe fruits of most of the species are consumed as such since time immemorial. Marula is found both naturally grown and cultivated (Fig. 3.3). Archaeological evidence suggests that the fruits of marula (*Sclerocarya birrea* subsp. *caffra*) were known and consumed by humans in southern Africa as far back as 9000 BC. It is the most widely

(a) (b)

Fig. 3.3 (**a**) Marula tree grown near Skukuza in the southern Kruger National Park, Mpumalanga, South Africa. **Attribution:** Nicolas Raymond from Bethesda, Maryland, USA [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)] https://upload.wikimedia.org/wikipedia/commons/1/16/Kruger_Park_Scenery_HDR_%287645852578%29.jpg. (**b**) Marula fruits collected in Ongwediva, Namibia **Attribution:** Pemba.mpimaji [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)] https://upload.wikimedia.org/wikipedia/commons/a/a5/Marula_fruits_Ongwediva_March_2016.jpg

consumed fruit among rural masses. An alcoholic drink is also prepared from its fruit. Shackleton et al. (2002) reviewed all kinds of *marula* uses in folk life. The elephants also pluck the fruits and eat because of their alcoholic contents. Surprisingly, they never damage a marula tree.

Monkey oranges (species of *Strychnos*) are other fruit trees yielding delicious fruits in Kwango and Caprivi regions of Namibia and in Zimbabwe; the fruits are used to prepare juice and jam on commercial scale. Because of drought, *Berchemia discolor* is one of the most preferred fruit trees in the Katima Mulilo region. The manketti (*Schinziophyton rautanenii*) has stood as the tree of difficult times in the Kavango Region. *Annona senegalensis*, *Diospyros mespiliformis*, *Friesodielsia obovata*, *Grewia* spp., *Parinari curatellifolia*, *Securinega virosa*, *Syzygium cordatum*, *S. guineense*, *Vangueria infausta*, *Vangueriopsis lanciflora*, *Ximenia americana* and *Ziziphus mucronata* are among many others which are consumed raw when ripe in the southern African region. *Adansonia digitata*, *Parkia biglobosa*, *Tamarindus indica*, *Vitellaria paradoxa* and *Ziziphus mauritiana* are consumed and cultivated in dry West Africa.

2. **Nuts or kernels consumed raw or roasted or made into porridge**: Dried kernels of *marula* (*S. birrea*) and *manketti (Schinziophyton rautanenii*); dried fruits of *Berchemia discolor*, *Diospyros mespiliformis* and *Parinari curatellifolia*; arils of *Guibourtia coleosperma* and roasted seeds of *Kigelia africana*, *Bauhinia thonningii* and *Schotia afra* are consumed by rural people most of the time by making porridge, and dried fruits of *Grewia flava*, *G. flavescens* and *G. retinervis* are soaked in water, mashed and eaten as porridge. The white pulp inside the hard, woody shell of *Adansonia digitata* fruit is eaten raw and is considered that it makes one fatty. The fruits of *manketti* and *matu* (*Strychnos pungens*) are used to make porridge. Manketti fruits are cooked, its fruit pulp is pounded into flour that is used to make porridge, and it can be mixed

with juice of *matu*. Cooking a mixture of pounded *eembe*, *marula* kernels, water and salt can make the traditional cake/bread. The kernels of false mopane (*Guibourtia coleosperma*) can be put on hot ashes to separate the outer part from the inner. The latter can either be cooked and eaten like that or made into a kind of *peanut butter* by mixing it with peanuts, frying and pounding it. Traditional *bread* can be made using either a mixture of roasted *manketti* kernels and maize or *mahangu* and *Berchemia*. The ingredients are pounded and cooked with water. Nuts of *Vitellaria paradoxa* are transformed into butter used for cooking in West Africa.

3. **Edible oil**: Rural population most commonly uses manketti and marula oils as edible oils. A kind of cooking oil is extracted from the fruit of *nonzwe* (*Ochna pulchra*), which can be stored for about a year.
4. **Jam and jelly:** Marula is widely used to prepare the traditional jam from its fruits. The fruits of monkey orange are made into delicious jam. A jam is made out of *eenkwiyu* (*Ficus sycomorus*) and marula fruits by cooking them with sugar or by some other traditional method. The fruits of eenkwiyu make a tasty *ombike.* The fruits of *Ximenia caffra* make a tart jelly. The fruits of *Grewia* are mixed with fresh milk to make it into a kind of yoghurt. The pulp of *Vangueria infausta* is used to make puddings, and when mixed with a little sugar and water, it makes a good substitute for apple sauce. Fruits of monkey oranges (*Strychnos* spp.) and *eembe* (*Berchemia discolor*) can easily be transformed into juice and jam of commercial value.
5. **Beverages and alcoholic drinks:** Fruits of marula, manketti (kernels), *Grewia flava*, *G. bicolor*, *Dialium engleranum*, *Diospyros mespiliformis*, *Parinari curatellifolia*, *Garcinia livingstonei*, *Berchemia discolor*, *Strychnos cocculoides* and *Ziziphus mucronata* are extensively used for preparing alcoholic drinks. Fruits of *Adansonia digitata* soaked in water make a refreshing drink. Fruits of *Syzygium guineense* are used to prepare a kind of drink. Powdery pulp of *Dialium engleranum* mixed with water makes a refreshing drink. Arils and red skin of *Guibourtia coleosperma* removed with warm water make a kind of beverage. Young fruits of *makami* palm (*Hyphaene petersiana*) make an intoxicating drink. 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.
6. **Crafting and thatching**: Leaves of *makami* palm (*Hyphaene petersiana*) and wild date palm (*Phoenix reclinata)* are widely used for making traditional storage baskets and thatch material for huts.
7. **Fencing**: Wood of many indigenous fruit tree species is part of the fencing of households.
8. **Ethnomedicinal/ethnoveterinary and other uses*:*** Many IFTS are used in traditional medicines for treating various ailments including routine stomach trouble, serious diarrhoea, malarial fever, cough and cold and many other diseases. Some IFTS with ethnomedicinal and other minor uses have been reported by Palgrave (1983) and Leger (1997).

3.4.2.3 Commercial Uses of Important Species

The biggest single formal market for indigenous fruits is the factory Phalaborwa in South Africa that produces marula pulp for use in *Amarula liqueur*. It buys between 2000 and 3000 tonnes of marula fruit in a year. In Namibia, there is a limited formal market for marula kernels used to produce cold-pressed crude oil for international cosmetic markets. Currently, this is owned and controlled by the Eudafano Women's Co-operative (EWC), which is a registered community trade supplier to the Body Shop. Not only these two commercial products are produced from marula, but also it has been shown that marula fruits can also be transformed into juice and jam of commercial importance.

Another IFTS of commercial importance are monkey oranges—*maguni/matu* (*Strychnos cocculoides* and *S. pungens*). A formal market for monkey orange fruit has been created by the Namibian company that makes *maguni liqueur*, at present with a limited market of 5 tonnes a year. PhytoTrade Africa recently facilitated the supply of monkey orange fruit samples to a South African company with a large international market. This has created a hope of a much larger market in due course of time. Both a low-alcoholic (beer) and a high-alcoholic (*kashipembe*) drink can be made from the fruits. It has been proved that *maguni* and *eembe* (*Berchemia discolor*) fruits can be transformed with success into juice and jam of commercial importance. Juice can also be prepared from fruits of *mulutuluha* (*Ximenia americana*). Cooking oil of commercial importance is prepared from kernels of manketti and fruits of *nonzwe* (*Ochna pulchra*).

Kashipembe of commercial importance can be prepared from *eembe* fruit, manketti/*nongongo* (*Schinziophyton rautanenii*) nuts and *nonsimba* (*Dialium engleranum*) fruit. Fruit pulp of *Adansonia digitata* is exported from southern Africa and Senegal. A strong alcoholic drink (*ombike*) of commercial importance can be prepared from fruits of *eenyandi* (*Diospyros mespiliformis*) and *enkenkete* (*Ziziphus mucronata*). Palm wine (*omalungo*) can be prepared from makalani (*Hyphaene petersiana*) palm. Thus, there are several IFTS with commercial importance. But we cannot depend solely on availability of fruits from natural forests. We would have to domesticate these potential trees and grow them on suitable sites for commercial exploitation.

3.4.3 Preferred Species and Their Potential for Domestication

Historically, researchers with various degrees of self-interest have largely chosen which species of indigenous fruit trees should receive their attention. Such subjectivity has led to suboptimal use of resources, lack of planning and attention. The farmers based their preferences on the following factors:

- Availability of the fruit species in the area
- Food security especially during famine years
- Ability of fruits to generate income both in cash and kind
- Ability of fruits to be processed into various products

- Ability of the fruits to be processed and stored for later use (e.g. due to its hard shell, *Strychnos cocculoides* and *Diospyros mespiliformis* were reported to be easily stored and transported)
- Personal satisfaction when the fruits are consumed

Though the most preferred species are widely distributed in the local forests, all the preferred species are not found in all the localities. As per the survey conducted through participatory approach in Namibia (du Plessis and Den Adel 2003), it was clear that marula (*Sclerocarya birrea*) was predominant in natural sites of Oshikoto, Oshna, Ohangwena and Omusati and bird plum (*Berchemia discolor*) in Oshna, Ohangwena, Omusati and Caprivi while monkey oranges (*Strychnos cocculoides* and *S. pungens*) in Kavango and Caprivi regions. Though there are many useful IFTS found naturally distributed in forests of different regions of Namibia, their preference differs in different localities depending upon the preferences of the people. Marula (*Sclerocarya birrea*), bird plum (*Berchemia discolor*), monkey oranges (*Strychnos cocculoides*) and manketti (*Schinziophyton rautanenii*) are among most popular and preferred species. The fruit of manketti is consumed as dry nut and is not fleshy and juicy; therefore, the other three are identified as three most preferred species for domestication in north-central and north-eastern regions of Namibia. In the Kavango Region, *Strychnos cocculoides*, *S. pungens* and *S. spinosa* were in abundance and the most preferred fruits. These are even sold in local as well as urban markets. Manketti (*Schinziophyton rautanenii*) was also a preferred species for preparing local drink from its nuts. In the north-east, near Katima Mulilo, *Berchemia discolor* was the most preferred species along with species of *Diospyros*, *Grewia* and *Parinari curatellifolia*. Besides these, *Vangueria infausta*, *Azanza garckeana*, *Adansonia digitata*, *Ximenia americana*, *X. caffra*, *Ficus sycomorus*, *Vitex payos*, *V. mombassae*, *Syzygium cordatum* and *Garcinia* spp. are quite frequently used in different regions.

Nongongo (*manketti*) was rated as the most important indigenous fruit (tree) in Mile 20 of the Caprivi region mainly because one can survive on that tree only. Its products can be stored for years and kept for times of hunger. The nuts can be stored for 3–4 years. *Nonsivi* (*Guibourtia coleosperma*) was seen as important also because its main product can be stored for a year and eaten in times of hunger. *Maguni* (*Strychnos cocculoides*) is important because the tree carries a lot of fruits, which are highly appreciated because of its taste. The problem however is that the fruits cannot be stored well. One can keep them only 1–2 weeks after collecting. Kalahari podberry/*nonsimba* (*Dialium engleranum*) was rated high as well because of its long storage capacity. It was said that fruits could stay on the tree and be used for at least 2–3 years. The Kalahari podberry only bears fruits every 2–3 years. *Nonzwe* (*Ochna pulchra*) is seen as an important tree, mainly because of the cooking oil one can extract from the fruit and keep for about a year. In Kasheshe, *Berchemia* was rated as the most important tree, because of its taste, long storage, nutritional value and abundance in the area. It was also said that *Berchemia* is important because it is harvested before crops are ready and can therefore help people survive in periods of hunger. *Grewia* was rated second most important, because of the sweetness of the fruits and its abundance in the area. Its fruits can be eaten fresh, dried, and mixed with fresh milk to make it into a kind of yoghurt. *Ximenia* is relatively abundant, and its fruits can be eaten fresh or made into a juice. The main disadvantage of *Ximenia*, however, is that both the fruits and the juice must be consumed immediately. *False mopane* fruits can be made into a relish for meat and a kind of peanut butter, and its stamped kernels can be cooked and eaten.

In Eefa, *eengongo* was rated as the most important fruit tree in the area, because of its many uses and cultural importance. Its marula wine and cooking oil are very much appreciated, and people also eat the fruits fresh, make a juice and a porridge out of it, eat the kernels fresh, mix them with other food, make a soup out of it and eat the leftover kernel cake after oil processing. *Eembe* was rated important mainly because of the reason that people like the taste of the fruit and can store the fruits dry for at least 6 months. *Berchemia* fruits are eaten fresh and dried, they can be used to make strong alcoholic liquor (*ombike*) and one can make a *Berchemia*/marula cake. *Eenyandi* can be eaten fresh as well as dried. One can make porridge out of the fruits and produce a low-alcoholic (*omalovu*) and strong alcoholic drink (*ombike*). *Eenkwiyu* fruits can be eaten fresh and dried and be made into a very tasty *ombike*. Some people know how to make *eenkwiyu* jam. *Eendunga* fruits can be eaten dried or made into *ombike.* Some people used it to make palm wine (*omalunga*), but the tree dies in the process. Palm leaves are used for making baskets and mats, and the branches are often used as fencing material. *Enkenkete* fruits are only used for making *ombike in* Ohangwena, Omusati and Oshikoto regions of Namibia.

In the Kavango Region, *Strychnos cocculoides*, *S. pungens* and *S. spinosa* were in abundance and the most preferred fruits. These are even sold in local as well as urban markets. Manketti (*Schinziophyton rautanenii*) was also a preferred species for preparing local drink from its nuts. In the north-east, near Katima Mulilo, *Berchemia discolor* was the most preferred species along with species of *Diospyros*, *Grewia* and *Parinari curatellifolia*. Besides these, *Vangueria infausta*, *Azanza garckeana*, *Adansonia digitata*, *Ximenia americana*, *X. caffra*, *Ficus sycomorus*, *Vitex payos*, *V. mombassae*, *Syzygium cordatum* and *Garcinia* spp. are quite frequently used in different regions.

Although bush fires are common, and obviously destroying a large part of the natural resources in the area, people on general felt that the number of indigenous fruit trees had increased in short period, especially *Berchemia*, *Grewia* and manketti. In their tradition, it is forbidden to cut down fruit trees for construction, fencing or firewood, but now, people use trees for these purposes also. In the north-central regions, most indigenous fruit trees are tenured by people and grow either at homesteads (*egumbo*), crop fields (*epya*) or in the woodland areas within farms (*ekove*). In Onkani, only *mopane* trees grow naturally, with other species like marula, *Berchemia* and *Diospyros mespiliformis* increasing with the immigration of people. In Eefa, the most abundant indigenous fruit tree species both on- and off-farm is *Diospyros mespiliformis*. Marula, *Berchemia* and makalani palm trees are less abundant and mostly grow in crop fields and homesteads. Small marula and *Berchemia* trees are often protected if found in the homestead. When homesteads move, the trees are left and found in the crop fields. In general, there is little natural regeneration of trees in community lands.

Uapaca kirkiana, *Parinari curatellifolia*, *Strychnos cocculoides* and *Sclerocarya birrea* were identified by farmers and stakeholders as priority species in the southern African regions, and the five most preferred species in different countries of this region are shown in Table 3.9 (Franzel et al. 2008). *Adansonia digitata*, *Parkia biglobosa*, *Tamarindus indica*, *Vitellaria paradoxa* and *Ziziphus mauritiana* are the most preferred species for domestication in dry West African Sahel, and some projects have been initiated to popularise them (Raebild et al. 2011).

Most of the preferred IFTS have potential for domestication. Many of these can be propagated successfully from seedlings raised in nursery or from cuttings or grafting. According to social survey conducted (du Plessis and Den Adel 2003) in Onkani, Eefa and Mile 20 in Namibia, many community people planted marula using seeds, seedlings and truncheons. These propagules were often selected on the quality of the fruits (taste and juicy nature of the fruits and number of kernels in the seeds) of the mother tree. All the planting methods were successful, but planting through truncheons had more advantages. It makes trees fruit faster (some after 3 years); one can be sure that it is a female tree and that the traits of the tree and its fruits are identical to the mother tree. Manketti also could be planted from truncheons. *Berchemia* could not be grown from truncheons. It could be grown from seeds, which were also selected on the quality of fruits of the mother tree. A major advantage of planting *Berchemia* was said to be the fact that one can be sure that the tree will bear fruits; the disadvantage, however, is that it takes a long time before they start fruiting. People in Onkani informed that they could grow *Diospyros* within the homestead, and a few seedlings would then be transplanted into the fields. Most trees found outside the homestead were said to be there because of the shifting of homesteads. They also planted figs (*Ficus* species) from stem and root cuttings. The survey results of Kasheshe show that half of the respondents had tried to plant either *Berchemia* or manketti or both. Manketti was planted using truncheons and *Berchemia* with seedlings or seeds, and most of them planted the trees in the homestead. Half of the respondents had also looked after young trees, especially *Berchemia*.

Raebild et al. (2011) reported that in West African Sahel, grafting was successful in *Adansonia digitata* while in *Parkia biglobosa* the rate of success was low and raising from cutting was possible. *Tamarindus indica* could be propagated through grafting, cutting and layering. In *Vitellaria paradoxa*, grafting and layering technologies were developed successfully, and in *Ziziphus mauritiana*, both rooted cuttings and grafting were found successful.

Though there is success in vegetative propagation of IFTS, the knowledge of genetic parameters, especially of fruit traits, is almost absent, but the characterisation of genotypes is underway for some of species in West African Sahel (Raebild et al. 2011). Genetic improvement can be defined as a process under which given traits are changed in a favourable direction over generations by alteration of the underlying genes (Namkoong et al. 1988). Further, Eriksson et al. (2006) stated that among the initial steps required involve identification and selection of superior provenances

Table 3.9 The most preferred IFTS for domestication by farmers of some African countries [percent of households mentioning the species (value in parenthesis is average preference scores out of 10, for those households mentioning the species)]

Species	Nigeria	Cameroon	Ghana	Malawi	Tanzania	Zambia	Zimbabwe[a]
Adansonia digitata				12 (8.5)	1 (8.0)	10 (9.5)	3
Alstonia boonei		63 (3.6)					
Anisophyllea boehmii						75 (7.9)	
Annona senegalensis				19 (8.1)	1 (7.0)	5 (8.4)	7
Annona squamosa			58 (3.5)				
Artocarpus communis			67 (4.5)				
Azanza garckeana				20 (6.6)		11 (5.4)	52
Baillonella toxisperma		77 (6.0)					
Chrysophyllum albidum	56 (6.8)		46 (3.0)				
Dacryodes edulis	64 (6.2)	67 (4.6)					
Dacryodes klaineana			25 (1.9)				
Dennettia tripetala	30 (3.7)						
Diospyros mespiliformis						8 (8.6)	28
Entandrophragma cylindricum		60 (2.6)					
Flacourtia indica				29 (7.4)	3 (7.0)	19 (6.5)	26
Garcinia afzelii			29 (2.0)				
Garcinia kola	39 (4.6)						
Guibourtia demeusei		37 (3.4)					
Irvingia gabonensis	86 (7.8)	86 (6.0)					
Milicia excelsa	64 (5.8)	37 (1.8)					
Newbouldia laevis	30 (3.0)						
Ocimum gratissimum	11 (2.5)						
Parinari curatellifolia				55 (8.4)	43 (8.9)	80 (9.0)	57
Physalis peruviana				2 (6.5)		35 (4.7)	
Raphia spp.		23 (1.5)					

(continued)

Table 3.9 (continued)

Species	Nigeria	Cameroon	Ghana	Malawi	Tanzania	Zambia	Zimbabwe[a]
Ricinodendron heudelotii		67 (4.1)	42 (1.9)				
Solanum indicum			33 (1.8)				
Spondias mombin			42 (1.8)				
Strychnos cocculoides				32 (7.0)	64 (8.2)	52 (7.7)	78
Strychnos pungens						16 (5.0)	31
Synsepalum dulcificum			42 (1.8)				
Syzygium guineense				11 (7.4)	1 (8.0)	39 (5.4)	28
Tamarindus indica				10 (5.9)	33 (8.9)	7 (8.3)	
Tetrapleura tetraptera			54 (2.9)				
Treculia africana	28 (3.9)						
Uapaca kirkiana				77 (9.3)	53 (9.3)	85 (9.5)	70
Uapaca nitida				1 (1.0)		35 (6.0)	
Vangueria infausta				19 (7.3)	16 (6.5)	3 (9.0)	4
Vernonia amygdalina	62 (5.6)						
Vitex doniana				8 (6.4)	26 (8.1)	1 (5.5)	
Vitex mombassae					46 (9.0)	1 (5.0)	
Vitex payos				1 (7.0)			34
Ximenia americana				7 (7.6)	1 (6.0)	27 (4)	

Source: Modified from Franzel et al. (2008)
[a]Preference score not available

through series of testing. This is followed by the breeding phase where superior genotypes are crossed by either crossed or random mating and the recurrent phase where progenies from these crosses are tested in the field and new selections made, crossed and evaluated over successive generations. This, however, requires long period. Knowledge of the heritability and the phenotypic variability for different fruit characters is, therefore, important in order to determine which traits are worth selecting for. Based on selected commercial cultivars of several tropical IFTS, Yao and Mehlenbacher (2000), Hardner et al. (2001), Thaipong and Boonprakob (2005), Silva et al. (2007) and Raebild et al. (2011) reported large heritability in fruit size or kernel weight.

3.4.4 Domestication Strategies

The most important aspect of domestication is the availability of accredited germplasm in sufficient quantity and at reasonable cost. The improvement of IFTS entails the applications of silvicultural, horticultural and tree-breeding skills to obtain the most valuable domesticable fruit trees as quickly and inexpensively as possible. In the process, farmers must be involved in collection of superior germplasm through appropriate selection process, propagation and dissemination in participatory mode. Suitable number of high-standard nurseries must be established for both propagation and skill development. The domestication programme is both market-oriented and farmer-led, but it has both research and developmental components also. These aspects are closely linked but need different approaches. The main goal of the developmental component is to obtain suitable fast-growing trees that can give early returns to the farmers, thereby accelerating wider adoption. The research goal is to ensure a solid scientific basis for domestication process, whereas the production goal is to ensure proper exchange and delivery of germplasm to farmers (Akinnifesi et al. 2004). The following basic steps are essential to follow:

- Identification of priority species involving regional experts, farmers and those who ensure marketing
- Selection and collection of superior phenotypes of individual trees from the wild involving experts and farmers
- Nursery development by raising the rootstock or vegetatively or by seeds and generating sufficient germplasm of the concerned species
- Management or cultivation on-station and on-farm
- Dissemination and adoption of planting materials and knowledge through literature and training
- Training and skill development for value addition
- Raising plantation
- Harvesting, value addition and marketing

3.4.5 Transformation

The success of domestication of IFTS will depend on nutritional and transformation value (into juice, jam and jelly) and economy of the produce. In an attempt to domesticate and improve IFTS in Botswana, Mateke (2000) analysed the nutritional composition of selected fruit trees. It was obvious from the data that marula fruit and manketti nut are rich in vitamin C and total carbohydrates and marula were found a potential candidate for juice production. African chewing gum (*Azanza garckeana*) is rich in fibre and protein contents and moderate amount of carbohydrates. Saka and Msonthi (1994) also determined chemical composition of the pulp and nuts of some indigenous fruits of Zomba with the intention of their domestication. *Ibbu* (*Vangueria infausta*) peel and pulp like marula also have commercial potential. The carbohydrate contents of *eembe* (*Berchemia discolor*) fruit pulp and peel are higher than that of either the marula or the *ibbu* fruits and make it good candidate for juice and fermented products. In a major economic breakthrough, Barion et al. (2001) prepared country wine from dried *eembe* fruit purchased from Katima Mulilo open market using commercial wine yeast. The fruit produced a wine with 8.6% alcohol content when no sugar was added. The addition of sugar increased the alcohol content of the wine, and all the batches produced dry wine. It was possible to use dried *eembe* fruit in the production of the country wine of acceptable standard. In the event that transportation of the ripe fruit proves difficult, it was recommended that the fruit be dried at the place of harvesting and later utilised in fermentation in wine making. The success of domestication of IFTS will solely depend on nutritional and economic improvement of the people. In New Zealand, the domestication process of kiwi fruits was made possible through the availability of commercial cultivators, planting materials and grower's organisations, which facilitated awareness through dissemination. In ICRAF, studies on marketing and the production economics of indigenous fruit tree products were initiated with following activities (Kwesiga et al. 2000):

- Identification of the factors determining the marketing chains in terms of prices and margins at the different marketing levels
- A better understanding of consumer's attitude and preferences for IFTS
- Description of the existing policy setting and its influence of the marketing of IFTS
- Determining the contribution of IFTS to household income and food security of small-scale farmers
- Access of the economic performance of investments in planting IFTS by small-scale farmers taking into account uncertainty in biological and economic parameters
- Evaluating the contribution of technological improvements in the multiplication and management of IFTS

These studies indicated that although IFTS may contribute substantially to household income and food security, there is a wide range of policy issues that need to be addressed, for example, government policies on concessions or subsidies and the interpretation of the laws about indigenous fruits as communal property or otherwise. To ensure food security of the local people, the proper chemical and nutrient analysis of the fruits and their products is essential. Besides being the sources of everyday food, many of the IFTS provide processed products such as jam, juice and alcoholic beverages, which fulfil the local demands and also generate cash. Marula (*Sclerocarya birrea*), *Ziziphus mauritiana* and *Uapaca kirkiana* are probably the best examples of fruit trees that have become important in the production of commercial beverages in Malawi, South Africa and Zambia.

3.4.6 Products Marketed and Marketing Systems

For the first time ever in Namibia, marula juice (for *omaongo* production) was extracted mechanically using small hydraulic presses designed by Katutura Artisans' Project (KAP) and disseminated by CRIAA SA-DC. The presses far exceeded expectations under field conditions. Some operators achieved up to 200 l a day—more than 300% the predicted daily production. Rolf Behringer of the Solar Stove Project at Valombola Vocational Training College developed a prototype of a solar batch pasteuriser. Once the prototype is scaled up, it can be combined with the small juice press into a technology package theoretically capable of producing around 50 l of pasteurised marula juice a day. This will enable producers to sell *omaongo* in local or national markets at any time of the year (du Plessis 2002).

Den Adel (2000) conducted other interesting socio-economic survey regarding use of marula products for domestic and commercial purposes by households in north-central Namibia, where marula is considered a tree of life. The community people use the tree and its fruits in so many ways as discussed earlier. The importance stretches from the social to the cultural, the economical and the nutritional aspects. The survey results clearly showed that the use of marula products in north-central Namibia and elsewhere in southern Africa is very common. One hundred percent of the interviewed households make marula wine, juice, cooking oil and a kernel soup, and they mix the kernels with other food, and almost all the households eat the fruits, the kernels and the cake and use the marula wood as the source of fuel. People sale marula products and use the cash for paying school fees of children, hospital expenditures, basic goods and supplementary sources of food. The existing marketing of indigenous fruits and their products is informal and multifaceted. Different levels of 'marketing' typically coexist.

Marula might be more valued as a resource, but bird plum (*Berchemia discolor*) is the favourite fruit, eaten by everyone when in season and used for jam and cake and *ombike* distillation. When dry, it is sold in informal market for about N$ 10 per kg. After several years of inconclusive market exploration, a serious and well-resource development partner in the form of a major multinational has finally taken an active research and development interest in manketti and *Ximenia* oil. The production of *Ximenia* oil in Namibia was systematically studied for the first time (du Plessis 2002), and it is possible that it may proceed to a significant commercialisation. There is a need for a better understanding of the distribution and potential production of *Ximeni*a in Namibia and for carefully differentiated collection of various species and subspecies for comparative analysis.

It is likely that bigger markets will be created for baobab (*Adansonia digitata*) and *Kigelia africana*. There are at least four small enterprises in neighbouring countries producing baobab oil. The Body Shop sells Baobab Bath Oil. In Namibia, baobab is only common in parts of western Omusati region and also reported to be found in north-eastern Otjozondjupa and parts of Caprivi. The potential of *Kigelia* is much larger than the current demand. It is easy to grow and starts fruiting after 7 years. du Plessis (2002) in his report submitted to the Indigenous Plant Task Team gave a brief and meaningful information regarding scope of commercial exploitation of some priority species. The Department of Food Science and Technology in University of Namibia has already been contributing and may contribute further to make the fruit products (like jams and jellies, juice, beer, wine) from preferred indigenous fruit trees of commercial acceptance.

It is clear from the above account that marula (*Sclerocarya birrea*), bird plum-eembe (*Berchemia discolor*), monkey orange (*Strychnos cocculoides*), manketti (*Schinziophyton rautanenii*), ibbu (*Vangueria infausta*), baobab (*Adansonia digitata*), *Ximenia* spp. and *Kigelia africana* have commercial potential in Namibia and are the forerunner candidates for domestication. These may play an important role in rural economy. As manketti nut is not consumed as desert fruit, therefore, the remaining IFTS are most suitable preferred indigenous fruit trees. Research efforts are also needed to find commercial uses of *Diospyros mespiliformis* and *Parinari curatellifolia* fruits, which are already consumed, stored and transformed in various products by the rural people.

3.4.7 Nutritional Value of Fruit Trees

Data on chemical composition of fruits and kernels (Table 3.10) of some indigenous fruit trees from different resources (Shone 1979; Arnold et al. 1985; Wehmeyer 1986; Saka and Msonthi 1994; Keya et al. 2000; Chadare et al. 2009; De Caluwe et al. 2009, 2010) show that many indigenous fruits are important sources of proteins, carbohydrates and water. Some are important sources of energy. The energy content of fresh fruits of some species like *Schinziophyton rautanenii*, *Vangueria infausta*, *Parinari curatellifolia*, *Ziziphus* spp., *Grewia* spp. and *Hyphaene petersiana* is superior to that of *Sclerocarya birrea* and other commonly marketed fruits juice in southern African countries such as *guava* juice. Others

Table 3.10 Chemical composition of some indigenous fruit tree species (compiled from various sources)

Species	*Berchemia bicolor*				*Hyphaene petersiana*	*Sclerocarya birrea*				*Schinziophyton rautanenii*		*Strychnos cocculoides*	*Strychnos pungens*
Component %	Raisin	Fresh fruit	Peels/pulp	Shell/kernel	Fresh fruit	Fresh fruit	Peels	Pulp	Kernel/nut	Fresh fruit	Nut	Fresh fruit	Fresh fruit
Moisture	18.4	78.8	17.8	7.5	6.6	85.0	74.2	84.5	8.7	8.6	4.2	80.4	72.1
Ash	2.8	1.0	3.5	1.7	9.0	0.9	5.8	6.8	4.0	5.2	4.1	0.5	1.0
Protein	4.0	1.1	2.7	4.1	4.9	0.5	2.5	1.5	19.0	7.8	26.3	0.7	1.1
Fat	3.5	0.6	1.3	24.0	0.4	0.4	2.6	1.0	56.6	0.5	58.1	0.1	0.3
Fibre	69.6	2.8	5.6	64.5	9.6	1.2	15.0	8.9	18.0	2.9	2.2	0.9	6.2
Carbohydrates	20.1	15.7	86.8	5.7	69.5	12.0	74.1	81.7	2.33	75.0	4.6	17.4	18.9
Energy (KJ/100 g)	–	305	–	–	1265	225	–	–	2703	1410	2715	308	367
Minerals content (mg 100 g^{-1})													
Calcium	–	88.6	–	–	103	20.1	–	–	118.0	85.0	223	9.41	29.3
Magnesium	–	30.9	–	–	197	25.3	–	–	462.0	214	493	26.9	38.1
Iron	–	2.24	–	–	2.04	0.5	–	–	4.87	2.54	3.42	0.18	0.62
Sodium	–	6.04	–	–	–	2.24	–	–	3.81	2.39	3.35	0.89	2.00
Potassium	–	270	–	–	2560	317	–	–	601	2145	674	188	478
Copper	–	0.20	–	–	0.47	0.7	–	–	2.81	1.3	2.53	0.07	0.25
Zinc	–	0.27	–	–	0.56	0.01	–	–	5.19	1.68	3.84	0.08	0.34
Manganese	–	–	–	–	–	–	–	–	–	–	–	–	–
Phosphorous	–	40.1	–	–	156	11.0	–	–	808	74.3	869	20.2	27.1
Vitamins content (mg 100 g^{-1})													
Thiamin	–	0.03	–	–	–	0.03	–	–	0.42	0.42	0.26	0.03	0.05
Riboflavin	–	0.06	–	–	0.10	–	–	–	–	0.13	0.22	0.06	0.42
Nicotinic acid	–	0.53	–	–	4.62	0.27	–	–	0.42	1.78	0.27	0.27	0.96
Vitamin C	–	50.3	–	–	19.70	194	–	–	–	27	Traces	6.7	10.7

(continued)

Table 3.10 (continued)

Species	*Vangueria infausta*				*Diospyros mespiliformis*	*Parinari curatellifolia*		*Pappea capensis*	*Ficus sycomorus*	*Bauhinia thonningii*	*Garcinia livingstonei*	*Guibourtia coleosperma*	*Ochna pulchra*
Component %	Fresh fruit	Peels	pulp	kernel	Fig (fruit)	Fresh fruit	Nut	Nut	Fig (fruit)	Seed	Fresh fruit	Seed	Fresh fruit
Moisture	64.4	26.9	–	10.8	82.7	64.6	2.6	1.9	82.7	82.7	83.9	9.1	63.2
Ash	1.4	4.3	2.8	2.0	1.1	1.5	2.7	2.3	1.1	1.1	0.4	1.9	0.9
Protein	1.4	2.7	0.4	21.0	1.4	1.6	28.7	26.3	1.4	1.4	0.80	14.3	6.3
Fat	0.1	0.3	4.3	37.6	0.5	0.5	58.0	65.1	0.5	0.5	0.30	8.0	7.5
Fibre	4.7	8.6	83.9	21.4	4.3	2.9	4.3	2.6	4.3	4.3	0.70	4.4	1.5
Carbohydrates	25.0	79.0	–	7.7	10.0	28.9	3.7	1.0	10.0	10.0	13.90	62.3	20.6
Energy (KJ/100 g)	498		–	–	210	533	2737	2919	210	210	258	1589	735
Minerals content (mg 100 g^{-1})													
Calcium	24.9	–	–	–	96.0	1.3	182	59.3	72.6	72.6	4.79	323	34.1
Magnesium	39.1	–	–	–	23.4	46.0	416	400	43.1	43.1	12.10	163	45.9
Iron	1.07	–	–	–	1.03	0.86	5.54	4.73	1.73	1.73	0.28	4.69	1.0
Sodium	28.1	–	–	–	13.7	4.63	4.39	6.08	5.70	5.70	6.92	20.3	1.74
Potassium	521	–	–	–	417	411	470	470	347	347	134	390	232
Copper	0.25	–	–	–	0.11	0.51	1.95	1.56	0.16	0.16	0.07	0.87	2.65
Zinc	0.24	–	–	–	0.21	0.1	3.06	3.73	0.38	0.38	0.19	2.7	1.85
Manganese	1.06	–	–	–	–	–	–	–	–	–	–	–	–
Phosphorous	36.6	–	–	–	27.8	26.6	466	411	33.4	33.4	20.30	198	74.6
Vitamins content (mg 100 g^{-1})													
Thiamin	0.04	–	–	–	0.01	0.04	0.68	0.71	0.07	0.07	--	–	0.04
Riboflavin	0.03	–	–	–	0.04	0.07	0.0	0.19	0.03	0.03	0.05	–	0.08
Nicotinic acid	0.61	–	–	–	0.24	1.28	–	3.79	1.41	1.41	0.40	–	0.90
Vitamin C	4.7	–	–	–	24.6	70.9	–	–	7.3	7.3	5.40	–	–

Species	*Ximenia americana*	*Ximenia caffra*	*Annona senegalensis*	*Ziziphus mauritiana*	*Ziziphus mucronata*	*Grewia retinervis*	*Grewia villosa*	*Grewia schinzii*	*Grewia flava*	*Grewia avellana*	*Grewia bicolor*
Component %	Fresh fruit	Fresh fruit	Pulp	Fresh fruit	Fresh fruit	Flesh + peel	Flesh + peel	Flesh +peel	whole fruit	Flesh + peel	Flesh + peel
Moisture	64.8	77.4	77.2	24.4	56.4	6.9	70.0	69.6	74.7	18.3	13.2
Ash	1.9	1.3	1.2	2.2	3.2	3.2	2.0	21	1.0	3.2	5.9
Protein	2.8	1.9	1.7	3.2	3.8	4.9	3.3	2.4	1.8	7.0	10.3
Fat	0.8	1.5	1.5	0.6	0.5	0.3	0.2	0.6	0.08	0.7	0.1
Fibre	1.2	0.9	3.9	2.4	2.1	15.9	1.9	1.8	1.6	28.2	13.5
Carbohydrates	28.5	17.0	14.5	60.9	34.4	68.8	22.6	23.5	20.8	42.1	67.0
Energy (KJ/100 g)	556	374	329	1198	659	1250	443	458	383	851	1302
Minerals content (mg 100 g^{-1})											
Calcium	7.58	8.17	41.1	157	129	150	–	–	62.4	150	268
Magnesium	31.1	19.0	83.8	38.5	58.3	173	34.6	63.9	61.1	112	317
Iron	1.27	0.49	0.74	0.73	0.95	3.8	0.9	0.9	1.08	1.78	5.92
Sodium	3.33	1.25	1.31	4.01	5.05	18.40	3.80	2.10	2.59	3.76	12.4
Potassium	718	558	465	1078	726	768	224	197	275	1050	1707
Copper	0.28	0.17	0.21	0.32	0.86	0.34	–	0.5	0.25	3.91	1.29
Zinc	0.68	0.29	0.26	0.39	0.52	1.11	–	–	0.47	2.84	2.59
Manganese	–	–	–	–	–	–	–	–	–	–	–
Phosphorous	34.2	35.4	375	101.0	51.4	54	41.0	41.8	51.3	91.8	181
Vitamins content (mg 100 g^{-1})											
Thiamin	–	0.03	–	0.05	0.06	0.03	–	0.03	0.03	0.17	0.20
Riboflavin	–	0.02	0.14	0.08	0.05	0.04	–	0.23	0.07	0.15	0.25
Nicotinic acid	–	68.2	0.82	1.96	0.71	1.61	–	–	0.62	1.28	3.47
Vitamin C	69.7	0.48	18.2	–	42.6	–	–	–	29.4	6.5	9.3

species are important sources of vitamin C. Examples include *Sclerocarya birrea*, *Parinari curatellifolia*, *Ximenia americana* and *Ziziphus mucronata*.

As discussed above, it is clear that adopting agroforestry models of cultivation, a smallholder can sustain the productivity of his fields and can produce edible fruits, vegetables, nuts, grains, rhizomes and tubers, forages, flowers, medicinal plants, other non-timber forest products, livestock products, honey, fuelwood for cooking, thatching material and other minor products of routine use on the same piece of land. Agroforestry technologies such as improved fallows (in western Kenya, southern Malawi and eastern Zambia) and alley cropping in moist regions and high lands have proved that degraded soils due to deforestation can be restored along with increasing productivity of farm as well as pasture lands. This all is interlinked with food security of the region. Even in the regions like southern Africa where agroforestry innovations are not well known, the role of indigenous fruit trees in food security and nutrition supplement in diet (as discussed earlier) has been well recognised. These results clearly indicate that agroforestry can play a vital role in the food security and accomplishing nutrient requirement to a greater extent in the developing world particularly in tropical Africa.

3.5 Community Agroforestry and Gender-Related Issues

With the escalating worldwide interest in agroforestry and true planting activities during the past couple of decades, several other terms like *community forestry*, *farm forestry* and *social forestry* have emerged. In these activities, the people's participation in tree planting need not associate with agricultural crops and/or animals as in agroforestry, but with social objective, these have equal importance in production. Thus, community agroforestry may be considered a practice using trees and their produce for livelihood of rural masses particularly in countries of southern Africa where indigenous fruits are commonly used by the rural communities for their livelihood. A community on communal/common land undertakes agroforestry tree planting or deliberately retaining of trees, with direct participation of local people or by processing the tree products locally. Collection of marula (*Sclerocarya birrea*) and manketti (*Schinziophyton rautanenii*) fruits and their processing for alcohol and other products for livelihood in southern Africa are classical examples of community involvement. Thus, all these labels jointly may be dealt as community agroforestry because these directly or indirectly refer to growing and using trees to provide food, fuel, medicine, fodder, building material (including grass for thatching in association with trees) and cash income. Akinnifesi et al. (2008c) have included socio-economic aspects of community plantations in Africa.

Gender issues, to a greater extent, influence agroforestry innovations in many African countries. African rural women by custom intend to produce the food crops in many societies, while men are interested to produce the cash crops. As food producers, women farmers are the key to reversing the crisis and increasing domestic production, but they lack power inside their own households. Food security analysists correctly argue that development strategies need to reach African smallholders to be effective, but they ignore the fact that the constraints facing women smallholders may be an important part of the problem. Gladwin et al. (2004) mentioned that 45% of the smallholders responsible for Zimbabwe's second Green Revolution (1980–1986) where women, and the women smallholders were responsible for adoption of hybrid maize in Malawi. Some ethnographic and policy researches (Rocheleau 1995) suggest that women have more limiting factors to adoption than men and an interaction between gender-related property relations and resource uses, users' groups, landscapes and ecosystem in western Kenya (a region where agroforestry had been practised since the 1600s). Scherr (1995) found that gender differences in agroforestry practices are still quite significant. In one study, men had 50% more trees on their farms and almost 30% higher tree density as compared to women farmers. Men tended to plant trees in cropland, while women's farms had more trees used primarily for fuelwood. Men also have dominance in decision-making at household level. This power differential between men and women lays the formation for gender bias from household-level decisions to policy-level decisions. Peterson (1999), however, reported from eastern Zambia that women do adopt improved fallow technologies because they understand their soils are depleted and they cannot afford to acquire the number of fertilisers required for their crops. In nursery raising, collection of non-timber forest products and taking value-addition trainings, women play very important and significant role in tropical African regions, hence contributing to poverty elevation and adopting agroforestry land use systems.

Kiptot and Franzel (2011), based on 104 studies conducted in different regions based on gender issues in agroforestry, emphasised that women who despite farming remain disadvantaged in the agricultural sector due to cultural, socioeconomic and sociological factors. Such factors include ownership and access to resources, land tenure systems, access to education and extension services, among many others. Women's participation is very high in enterprises that are considered to be women's domain, such as indigenous fruit and vegetable products and processing. In the *Vitellaria paradoxa* (shea)-growing region of Benin, 90% of women are involved in collecting nuts/fruits of the *shea* tree, while in Cameroon, women and children are also the main collectors of the leaves of *Gnetum africanum* which is used as a vegetable. In Zambia and western Kenya, no significant differences were found between proportions of men and women practising improved fallows. However, there were more women than men using improved fallows and biomass transfer in western Kenya and using fodder shrubs in central Kenya.

Although women are actively involved in agroforestry for fodder production, in application of woodlot technology and soil fertility improvement, their level of participation is low comparative to men. Female heads of households planted only half as many shrubs/trees as men. The lesser involvement reflects women's lack of resources, particularly land and labour, their heavy workload and perhaps also their greater aversion to risk. In initial agroforestry management issues such as hoeing and watering, women manage well. Another interesting feature was observed that the men are usually interested in trees for commercial purposes while women are more inclined to tree products for subsistence use such as firewood, soil fertility improvement, fodder and fruits. This is reflected in the tree attributes that women prefer. In Malawi, women in female-headed households considered trees that grow fast as their first choice, followed by trees with good burning qualities and that produce a lot of charcoal. In turn, men ranked trees that grow straight as their first choice, an indication that timber is their number one priority. As far as marketing of agroforestry products is considered, women are usually confined to the small retail trade, while men dominate the wholesale trade. Women traders also receive lower marketing margins than men. This is attributed to the fact that men usually have more stock than women, because they have access to more capital. Only 20% of the participants in the major market information systems of Kenya and Malawi are women maybe due to the reason that their literacy level is lower than men's. These disadvantages mean that women fail to benefit equitably from the growing national and international markets.

Policy interventions, especially in extension, are essential to empower women in this sector. In order to promote gender equity in agroforestry and to ensure that women benefit fully, Kiptot and Franzel (2012) and Kiptot et al. (2014) recommended various policy, technological and institutional interventions which include (1) facilitating women to form and strengthen associations, (2) assisting women to improve productivity and marketing of products considered to be in women's domain and (3) improving women's access to information by training more women extension staff, holding separate meetings for women farmers and ensuring that women are fully represented in all activities. Further, using fertiliser tree systems, they can minimise the input costs towards fertilisers.

3.6 Research Opportunities and Policy Issues

3.6.1 Research Opportunities

Agroforestry systems are complex in nature in which one component of a system has influence on the performance of the other components as well as the system as a whole. As discussed earlier under different agroforestry systems, the impacts of trees, shrubs, mulch, manure and litter on soil amelioration in terms of increasing organic carbon and availability of nutrients are well documented. The major types of positive or complementary interactions at the tree-crop interface are those relating to microclimate amelioration and nutrient balance. Microclimate amelioration involving soil moisture and soil temperature relations and microbiological advantages result primarily from the use of woody perennials for shade, as alley crops, for fruits or minor products or as live supports, live fences or windbreaks. Temperature, humidity and movement of air, as well as temperature and moisture of the soil, directly affect photosynthesis, transpiration, microbial activities in soil and the energy balance of the associated crops, the net effect of which may translate in increased yield. The increased productivity can easily be transformed into animal productivity with high nutritional and monetary value. The productivity of silvopastoral system (including animals) can be further increased through the transfer of manure as a fertiliser source and shade as a factor for increasing animal productivity. The magnitude of interactive effects between trees and other components of agroforestry systems depends on the characteristics of species, their planting density and spatial arrangement and above all the management of trees and crops. Other common management operation such as fertilisers, application of mulch and manure, cut-and-carry fodder systems and rotation or confinement of the animals can also be employed.

As discussed in text, agroforestry systems provide an opportunity for modifying nutrient cycling through management, which results in more efficient use of soil nutrients whether added externally or made available through natural processes. For example, the trees may mine uptake of nutrients from deeper soil horizon and made available to associate crops through litter fall, and symbiotic nitrogen fixation can be enhanced through tree-species selection and admixture. Another major management tool is the possibility of reducing nutrient loss through soil conservation and to manage water resources in a watershed particularly through suitable agroforestry practices. For example, vegetative barriers (forage grasses and woody perennials) across the slope are quite effective in soil and water conservation on a sloping land. Trees also play the important role of biodrainage in waterlogged situations, and alley crops help in checking runoff on highlands in high-rainfall areas and maintaining crop residues on soil surface for retaining soil moisture.

Agroforestry not only assures the sustainable production but also helps in biodiversity conservation. In developing countries of Africa, for the requirements of fuelwood, fodder, timber and thatching material for ever-increasing population, the pressure on natural forests is immense leading to deforestation. The anticipated magnitude of species loss has drawn worldwide attention, fuelling attempts to rapidly assess and conserve biodiversity. The strategy to conserve biodiversity includes establishment of protected area network and corridors with emphasis on appropriate levels of management; reduction of anthropogenic pressure on natural population by cultivating them elsewhere (including in agroforestry systems); programmes of augmentation, reintroduction and introduction of target taxa; and in situ techniques such as establishing botanical and zoological gardens and banks of pollen, seed, tissue culture, DNA, etc. Agroforestry can play vital role in conserving biodiversity in the following ways: (1) relieving direct pressure on natural forests; (2) direct cultivating of rare species (e.g. rare medicinal plants) in agroforestry systems as crop; (3) number of species automatically will increase under agroforestry system (particularly in multi-tiered homegardens) as compared to sole agriculture; and (4) the microbial population will be manyfold richer under good moisture, better water-harvesting processes, application of mulch, litter and mulch degradation and introduction of leguminous N-fixing trees. Recently, studies have shown that greater plant species diversity leads to greater productivity in plant communities, higher nutrient retention in ecosystems and greater ecosystem stability. The functioning of terrestrial ecosystems depends on soil biodiversity as many of the plant interactions take place belowground. Microbial communities inhabiting soil mediate key processes that control system nutrient cycling.

As is evident from several studies discussed earlier in this paper, tree plantations and silvopastoral systems improve soil organic matter and availability of nutrients. The soil microbial biomass is a labile fraction of soil organic matter and plays a crucial role in maintenance of soil fertility and availability of plant nutrients. Addition of organic matter favoured rich micro-biodiversity of soil and nitrogen mineralisation in a silvopastoral system on degraded soil. The microbial biomass carbon increased due to increase in the carbon content in the soil-plant system. Nitrogen mineralisation rates were found greater in silvopastoral system compared to only grass system, and the soil organic matter was linearly related to microbial biomass carbon, soil N and nitrogen mineralisation rates. The role of key functional groups of soil fauna such as termites and earthworms has been analysed in nutrient cycling, organic matter decomposition and formation of soil structure in different types of ecosystems, and the belowground plant dynamics (including litter decomposition) regulate the composition and functional role of soil organisms. Plant diversity and litter quality regulate diversity of soil organisms, community dynamics and soil microbial biomass. Thus, agroforestry is a tool for sustainable production and biodiversity (including of microbial) conservation.

The rapid increase in atmospheric concentration of CO_2 and other greenhouse gases since the onset of the industrial revolution in 1850 is attributed to change in the soil and biotic C pool. Soils of the tropics, constituting a major part of the soil C pool, have contributed considerably to the anthropogenic increase in atmospheric CO_2 pool resulting to global warming. During the last two decades, mean temperature of African continent has risen more as compared to the global temperature. Results of several experiments have shown rapid decline in soil organic carbon (SOC) content when natural ecosystems in the tropics are converted to arable and pastoral land use (Lal 2000). In one experiment, SOC content of the surface horizon from 1.7 to 2.0% under native vegetation declined to 0.8–1.0% within 10 years of cultivation (Lal 1997). Restoration of degraded soils is an important strategy of increasing SOC content and sequestering C within the terrestrial ecosystems. Relevant soil restoration measures include those which facilitate establishment of any vegetative cover that adds a large quantity of biomass into the soil. These include establishing trees, growing cover crops and raising multi-storeyed homegardens. Establishment of woody perennials can lead to soil restoration and enhancement of SOC pool. The rate of C sequestration through restoration of degraded soils may range from 200 kg ha^{-1} year^{-1} to 2500 kg ha^{-1} year^{-1} depending on the management and the potential of pool depletion (Lal 2000). In one study, it was found that under *Acacia nilotica*- and *Populus deltoides*-based agroforestry systems, the SOC contents were 48% higher than sole crop cultivation. Afforestation and agroforestry have tremendous potential for C sequestration not only in aboveground C biomass but also in root C biomass in deeper soil depths. Reforestation of about 19 million ha of most degraded lands with suitable trees and grasses/crops may sequester about 1 Pg C (Dagar and Swarup 2003). Thus, well-managed agroforestry systems particularly on degraded lands have tremendous potential of C sequestration in dry regions.

3.6.2 Policy Issues

Soil fertility depletion in smallholders' farms is one of the fundamental causes of declining per capita food production in Africa, and it has implications for food insecurity in many parts of the continent. Past efforts focused primarily on promoting wide-scale use of subsidised mineral fertilisers in southern Africa, but the increased cost of fertilisers has dramatically reduced the use of fertilisers. Planted tree fallows (improved fallows) have demonstrated great biophysical potential for improving soil fertility on smallholder's farms, but efforts to scale up their adoption to more farming households are constrained by lack of permanent ownership rights over land, incidences of bush fires and browsing of tree biomass by livestock. To resolve these institutional bottlenecks, some traditional authorities in Zambia enacted bylaws to prohibit these incursions. Ajayi and Kwesiga (2003) and Ajayi et al. (2003) conducted studies on implications of local policies and institutions on the adoption of improved fallows and indicated that the effectiveness of bylaws is influenced by many factors such as ambiguous interpretation of the bylaws, relying exclusively on moral persuasion to enforce the bylaws, lack of well-defined responsibilities and conflict of economic interest among different stakeholders within the communities. The patterns of distribution of benefits of an agricultural technology among various sectors of a community may be important factor that affects widespread adoption of a technology. They also stated that the policy dialogue among community members, increased awareness and diversification of options appear to be the way forward to improve the effectiveness of the bylaws. The farmers must be educated about diversification of agricultural options. For example, for increasing soil fertility, one should avoid the species palatable to animals, and livestock farmers should be encouraged to plant fodder species to feed their animals, thereby reducing the competition for improved fallow species during the dry season. The diversification options also include the use of live fences that not only prevent animals from intruding but also provide extra fruit or income to farmers. Madhura et al. (2003) while studying the potential for adoption of *Sesbania sesban*-improved fallows in Zimbabwe concluded that households with larger farm sizes with more family members working full time on farm and having draft power and access to cattle manure were in better position to adopt the technology.

In southern Africa, fruit from many indigenous fruit trees like marula (*Sclerocarya birrea*), *Uapaca kirkiana*, *Parinari curatellifolia* and *Strychnos cocculoides* are collected for household consumption and to generate income. Attempts are being made for their domestication, but the technologies for their propagation at large scale have not fully developed. This should be given priority in all national policies. A number of technical areas still require scientific investigations. Research must be directed to provide the information needed to develop strategies to respond to the projected trends in demand and opportunities for agroforestry in Africa. The following strategies and opportunities have been discussed by Kwesiga et al. (2003) and Akinnifesi et al. (2008b) for success of agroforestry in Africa:

1. Improving marketing and processing of agroforestry products in demand for urban and rural markets.
2. Diversification of agroforestry products and by-products such as high-values trees, indigenous and exotic fruit trees, medicinal plants, fodder for livestock and organic vegetable production. This will help small producers to develop their own processing and marketing channels (cottage industries).
3. Development and promotion of substitutes and supplements for costly imported inputs like inorganic fertilisers (e.g. growing protein-rich folders and nitrogen-fixing trees).
4. Options for mitigating the continuous degradation of the environment and loss of biodiversity (e.g. C sequestration through afforestation and agroforestry options).
5. International issues like mitigating global warming.
6. Development and implementation of strategies for large-scale dissemination of agroforestry technologies at the local level.
7. Training and capacity building in agroforestry among all major stakeholders.
8. Co-operation and partnerships with a broad range of actors.

Besides the above strategies and opportunities, the following points may also be added:

9. Legislation for stopping intentional and non-intentional burning of forests. For example, in the Kwango region (Namibia), community people have a notion that better thatch grass will be regenerated after burning of the old, and in the process, they burn the forest. In such instances, the forest guards should be strengthened and empowered through meaningful legislation.
10. Research efforts should be enhanced to domesticate the indigenous forest trees on degraded and bare lands and on pasturelands so that the pressure on natural forests may be reduced. For fuelwood and fodder, block plantations/fodder banks of suitable species may be raised on degraded lands.
11. Pasture should be improved by seeding with legumes during rainy season, and leguminous trees should be preferred for introduction on fallow lands.
12. Research gaps should be identified, and more research projects should be sanctioned to develop techniques of tree propagation and improvement. Indigenous fruit tree improvement programme should be further strengthened.
13. Fruit transformation training should be extended to rural women so that they can increase the income of their household.
14. Women would be made equal partners in decision-making policies.
15. Strengthening of extension programme so that the techniques developed should reach to the needy poor farmers.

16. Promotion of African/regional co-operation through technology and germplasm exchange, study tours and field visits, demonstrations of on-farm research, information exchange, trade and marketing of agroforestry products.
17. Financial supports form international organisations like the FAO and World Bank to generate technologies in the fields of indigenous fruit transformation, nutrition analysis of potential fruits and income generation potential of indigenous fruit, medicinal, fodder and timber species and their genetic improvement.

There are some constraints to wider adoption of agroforestry techniques in African countries, which need to be addressed by the planners, politicians, researchers and extension workers. Some of the constraints and issues are briefed here:

1. One intrinsic change lies in the long-term nature of the benefits to be derived from most agroforestry practices. Similar experience is found with most natural resource management practices. Farmer must be able to withstand initial years of low or negative profitability in order to reap longer-term economic profits. Access to credit, reliable tree seed supply and improved access to agricultural markets offering adequate prices would minimise this constraint (Kwesiga et al. 2003).
2. Another significant source of limitation is institutional—It lies with national agricultural extension services, which need to be greatly strengthened by offering more education and training to their personnel and resources.
3. Easy access to natural resources (forests) is another interesting issue. Most of the community people have access to thatching grasses, fruits and other forest produces; therefore, they do not take pains for domestication of indigenous fruit trees on their own farm. They must be educated and trained in the field of domestication and fruit transformation so that habit of income generation through fruit products on their own farm is inculcated in them.
4. Lack of improved germplasm—Very little efforts have been made in genetic improvement of indigenous fruit tree species and techniques of tissue culture, and tree improvement should get the priority so that plenty of good quality of germplasm may be available for propagation of preferred tree species.
5. Some second-generation issues are emerging such as growing incidences of pest and disease, water requirement for crops and fruit trees, reduced investment in agricultural sector, lack of availability of fertilisers and pesticides due to their cost and related policy shifts such as removal of agricultural subsidies (Kwesiga et al. 2003).
6. Poor infrastructure of marketing.
7. Traditional ways of processing of fruit products—Most of the farmers (mainly women) process their fruit products like extraction of juice and making of alcoholic drinks in their traditional way. They need extensive training in fruit transformation so that they can prepare commercial juice and jam. They must be made partners in commercial exploitation such as preparation of alcoholic drinks from wild fruits and nuts.

8. Capacity building—People need training at all levels (planners, foresters, extension workers, researchers and community people) for economic feasibility of agroforestry products.
9. Institutional and international collaborations—At times, one institute is not familiar about the work carried out in another. At national and regional levels, there must be inter-institutional collaboration particularly in processing and value-addition aspects. If need be, international collaborations are also needed to get knowledge and training in different fields especially in food-processing aspects.

Recognising the lessons learned that there are four critical conditions that encourage agroforestry, it should be beneficial to farmers and other land users, there must be security of land tenure, intersectoral coordination is essential and good governance of natural resources is crucial, FAO (2013) concluded that the guidelines provide ten tracks for policy action:

1. Spread the word—Raise awareness of the benefits of agroforestry systems to both individual farmers and global society.
2. Revise the context—Appraise and reform unfavourable regulations and legal restrictions.
3. Secure the land—Clarify land use policy goals and regulations.
4. Create a new approach—Elaborate new agricultural policies that take into account the role of trees in rural development.
5. Organise and synergise—Organise intersectoral coordination for better policy coherence and synergies.
6. Provide incentives—Create a clear context for payments for environmental services.
7. Develop markets—Strengthen farmers' access to markets for tree products.
8. Communicate the know-how—Enhance stakeholder information.
9. Include the stakeholder—Formulate or strengthen policy based on local people's needs and rights.
10. Govern wisely—Engage in good governance of rural activities.

It is expected that the actions outlined above will contribute to the formulation of coherent, interactive and proactive public policies that support the development of appropriate agroforestry systems in Africa.

3.7 Conclusions

Due to fast-growing population, many regions in tropical Africa are presently facing shortage of food, fodder and fuelwood. Deforestation, declining soil fertility and soil erosion are the crucial indicators of land degradation. Most of the dry regions experience food shortage due to low crop yields in the nutrient-depleted soils. There lies problem of cattle health due to scarcity of fodder especially during the dry season. Due to increase in cost of inputs, smalholders are not in a position to afford the application of fertilisers in their crop fields. Continuous cultivation has inevitably replaced shifting cultivation and the bush fallow systems, which were traditionally practised to rebuild soil fertility in the savanna of eastern and southern Africa.

In the area of soil fertility management, the focus must be on growing woody perennials in situ or on the transfer of biomass from one part of the farm to another. Improved fallow systems as alternatives to the traditional fallow practices have been developed using either coppicing tree species (e.g. *Gliricidia sepium*) which are grown in permanent association with crops or non-coppicing species (e.g. *Sesbania sesban*, *Tephrosia* species), which are grown in rotation with crops. Growing fertiliser trees in association with crops, particularly in rain-fed ecologies, has helped in increasing crop yield significantly, improving the soil and conserving soil moisture. In recent times, much emphasis has been placed on domestication of indigenous fruit trees and their value addition, and significant progress has been made in identification, raising nursery and plantations, processing, value addition and marketing of suitable fruit trees.

In the humid and subhumid areas of West Africa, alley cropping has been found ideal for sustainable production of crops and soil and moisture conservation. Other agroforestry options include domestication and processing of indigenous fruits to enhance family nutrition and income and fodder banks for supplementary feeding of dairy cattle. Low income at initial stage, resource management know-how, institutional limitations, lack of training of different stakeholders, irrational access to natural resources, casual approach to domestication programmes, lack of improved germplasm and technology like tissue culture for multiplication of germplasm, lack of irrigation facilities, poor infrastructure of marketing, removal of agricultural subsides, traditional ways of processing of fruit products and non-implementation of forest legislation are some constraints and issues of agroforestry adaptation. In addition, a number of technical areas still require scientific investigations. The widespread adoption of agroforestry technologies, supported by continued participatory research and dissemination, has the potential to achieve the goals of poverty alleviation, food security and environmental protection including C sequestration in wider regions of Africa. In the scenario of climate change, agroforestry-based smart agriculture is the most suitable option for sustaining yield, improving soil and mitigating climate change.

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4 Potential of Agroforestry to Enhance Livelihood Security in Africa

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Abstract

Agroforestry systems dot agricultural landscapes in sub-Saharan Africa (SSA), where they provide food, fuelwood, fibre, fodder and other products that are used at home or sold for income. Agroforestry also provides ecosystem services that are important and critical for improved livelihoods. By combining trees and/or shrubs with crops and/or livestock, agroforestry diversifies both farm and non-farm activities. This creates diverse livelihood strategies that help households to deal with recurrent shocks, such as droughts and lean periods, and can make livelihoods more sustainable over time. Based on the literature on agroforestry in SSA, we describe major tree-based systems that are widely practised in SSA and that have received much attention in terms of their contribution to sustainable livelihoods. We show that agroforestry systems are typically multifunctional, although the type of goods and services produced vary depending on the components of agroforestry and the way these are managed in the landscape. Broadly, agroforestry supports food production, health and nutrition, wood-based energy and income. We discuss the current state of knowledge, present case studies to provide the evidence base and highlight gaps in knowledge and barriers to harnessing agroforestry-based livelihoods.

Keywords

Biomass transfer · Fertilizer trees · Nutrition gardens · Rotational woodlots

4.1 Livelihood Systems in sub-Saharan Africa

4.1.1 Rural Livelihoods

Livelihood refers to the means by which people make a living. According to Chambers and Conway (1991), livelihood comprises people, their capabilities and their means of living, including food, income and assets. 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 (FAO 2019). In sub-Saharan Africa (SSA), rural livelihoods are directly linked to agriculture via small-scale processing and artisanal production and non-agricultural activities, such as wage labour, trading, hawking and service provision (Niehof and Price 2001). Agriculture, particularly farming and herding, is the main source of livelihood in rural Africa (Montpellier Panel 2013; Alliance for a Green Revolution 2017). Using 41 national household surveys from 22 countries in Africa, Davis et al. (2017) found that 92% of rural households are engaged in agriculture. In another study, on-farm sources of income accounted for 59–78% of the total household income in Malawi, Madagascar, Nigeria and Ghana (Davis et al. 2010).

Besides the above-mentioned two sectors, natural resources such as forests and woodlands play a central role in rural livelihoods in Africa. A review of the socio-economic contributions of non-timber forest products (NTFPs) to rural livelihoods in

SSA reported widespread reliance on NTFPs for subsistence and income (Timko et al. 2010). Examples of NTFPs commonly used in SSA include food and food derivatives (e.g. roots, fruits, edible seeds, kernels, edible leaves, mushrooms, insects and bush meat), medicines, fodder, gums and resins, and oils (Shackleton and Shackleton 2004; Timko et al. 2010; Hickey et al. 2016). People also collect bamboo, other grasses and palms for construction, weaving and handcraft productions (Timko et al. 2010). NTFPs are collected at minimum or no cost and provide a safety net during lean periods. However, they are seasonally available, collection is labour or time consuming and access to most forests is regulated.

4.1.2 Livelihood Diversification as an Option for Livelihood Security

Livelihood security connotes sustainable and adequate access to resources to meet basic needs (Frankenberger and McCaston 1998). Yet, approximately 70% of the people in SSA depend on land for their livelihoods (Montpellier Panel 2013; AGRA 2017) and have insecure livelihoods (Ellis 1998, 2000). Among these are the poor and marginalized communities whose survival is already at risk (Gray et al. 2016). Declining crop yields, production failures due to drought periods and lack of income are the leading causes of livelihood insecurity for these communities (UNEP 2015). Already Africa has the highest prevalence of undernourishment and food insecurity compared to other regions of the world (FAO et al. 2018). In 2017, an estimated 236.5 million people (23.2% of the population) were undernourished, while 345.9 million people (33.8% of the population) experienced food insecurity (FAO et al. 2018). It is at the heart of these eventualities that viable options for livelihood diversification are necessary for rural communities to attain their livelihood security.

Defined as the process by which rural families construct a diverse portfolio of activities and social support capabilities in order to survive and improve their standards of living (Ellis 1998), livelihood diversification is a common characteristic of rural smallholders in Africa (Ellis 2000). It occurs as diversification of the rural economy, which is a sectoral shift of rural activities from farm to nonfarm activities, or as individual or household diversification, which is an increase of the number of income-generating activities by individuals or households, regardless of the sector or location (Loison 2015). Livelihood diversification portfolios can consist of farming and nonfarming activities, include wage employment or self-employment, depend on how labour is compensated and accrue on-farm or off-farm, depending on the location where the activity takes place (Barrett et al. 2001; Loison 2015).

Asset, activity and income diversification are typical in livelihood strategies in rural Africa (Ellis 2000; Barrett et al. 2001). Most rural households have multiple sources of income (Ellis 1998), although agriculture remains important and, in most cases, the principal activity of poor households (Ellis 2000; Davis et al. 2010, 2017). In Africa, rural household diversification serves primarily as a strategy for coping with economic and environmental shocks but also as a means of enhancing income (Loison 2015). There is growing evidence that nonfarm sources contribute significantly to rural household income (Davis et al. 2017), in some cases up to 40% of average household income (Barrett et al. 2001; Haggblade et al. 2010). Nonfarm livelihood options that people resort to may include processing or transport of unprocessed agricultural and forest products (Barrett et al. 2001); small-scale business, such as trading and hawking; provision of services, such as transportation; and artisanal production (Niehof and Price 2001). Migration or transfers from networks in urban areas occur where there are no viable opportunities to diversify income activities (Loison 2015).

Livelihood diversification in Africa requires investment in improved farm practices and/or in nonfarm assets, depending on the options available for coping with shocks and income generation (Loison 2015). Currently, specialization in on-farm activities is common in rural Africa, practised by an average of 52% of households, and ranging from 33% of households in Kenya to 83% in Ethiopia (Davis et al. 2010). This means that the majority of rural households receive more than 75% of their income from a single source (Davis et al. 2017). Such households need to be able to generate cash, build assets and diversify across farm and nonfarm activities in order to use livelihood diversification to improve quality of life (Loison 2015). Agroforestry is one of the options that can diversify both farm and nonfarm activities. By creating diverse livelihood strategies, agroforestry can help households deal with recurrent shocks and lean periods and make livelihoods more sustainable.

4.2 Major Agroforestry Systems in sub-Saharan Africa

The variety of agroforestry practices found in SSA is wide. Agroforestry practices may consist of sequential practices in which trees and crops are grown in rotation (e.g. rotational woodlots and improved fallows) or annual relay fallows where fast-growing nitrogen-fixing leguminous shrubs are planted in a crop field at a time when annual crops (such as maize) have already been well established, usually within 2–4 weeks of crop sowing (Akinnifesi et al. 2010a), and tree crop intercropping—simultaneous practices in which trees and crops are grown together in various spatial arrangements (Cooper et al. 1996; Rao et al. 1998; Sileshi et al. 2007; Akinnifesi et al. 2010a). Simultaneous practices are the most common way in which trees are planted on farms. They may include trees on cropland (e.g. scattered trees on cropland or pastures, boundary planting and intercropping), hedgerow intercropping (alley cropping), multi-strata agroforestry systems (e.g. homegardens) and plantations of commercial crops under shade trees (Cooper et al. 1996; Rao et al. 1998; Sileshi et al. 2007).

Typically, agroforestry practices are multifunctional (Kuyah et al. 2016, 2017), although the type and magnitude of the goods and services produced vary depending on the components involved and the way these are managed in the landscape (Table 4.1). Based on the literature on agroforestry, major tree-based systems that are widely practised in SSA and that have received much attention in terms of their contribution to sustainable livelihoods are described.

Table 4.1 Major agroforestry systems and practices found in SSA and their contribution to livelihood benefits

System	Agroforestry practice	Goods and services	Contribution to livelihood benefits
Fertilizer tree	Alley cropping/ farming	Stakes, fuelwood and fodder; soil improvement, erosion control and pest regulation	Food production, income and fuelwood
	Relay fallow/ intercropping	Stakes, fuelwood, fodder and edible pulses (e.g. *Cajanus cajan*) and soil improvement	Food production, income and fuelwood
	Simultaneous intercropping	Timber, poles and fuelwood and soil improvement, wind regulation and microclimate improvement	Food production, income and fuelwood
	Sequential (improved) fallows	Fuelwood, stakes and fodder and soil improvement, pest regulation and erosion control	Food production, income and fuelwood
	Agroforestry parklands (perennial)	Food and food derivatives, fuelwood, timber, craft and medicines and soil improvement, microclimate improvement, shade for livestock and cultural benefits	Food production, cosmetics, health and nutrition, income, fuelwood, cultural benefits
	Biomass transfer (cut and carry system)	Stakes, fuelwood, fodder and soil improvement, pest regulation and erosion control	Food production, income and fuelwood
Fodder tree	Fodder (protein) banks	Fodder, stakes and medicines	Health and nutrition and income
	Silvopastures	Timber and shade for livestock and herdsmen, wind regulation and microclimate improvement	Health and nutrition and income
Fruit tree	Perennial crop orchards	Fruits and refugia for biodiversity	Health and nutrition and income
	Homegardens and agroforests	Food and food derivatives, medicines, cash crops, fodder, timber, fuelwood, refugia, in situ conservation of biodiversity, ornamental and shade	Food production, health and nutrition, income, fuelwood and cultural benefits
Firewood and timber	Rotational woodlots	Firewood, stakes and soil improvement	Fuelwood and income
	Smallholder timber	Timber and firewood	Fuelwood and income
	Live fences	Stakes and firewood and wind regulation, microclimate improvement, boundary demarcation, refugia and ornamental	Fuelwood, income and cultural benefits

(continued)

Table 4.1 (continued)

System	Agroforestry practice	Goods and services	Contribution to livelihood benefits
	Windbreaks	Timber, fuelwood and wind regulation, microclimate improvement, erosion control, refugia and ornamental	Income, food production, fuelwood and cultural benefits

4.2.1 Fertilizer Tree Systems

Fertilizer trees are defined as nitrogen-fixing woody perennials used for soil fertility improvement in arable lands and pastures (Sileshi et al. 2014). Fertilizer tree systems represent a paradigm shift in land use management by smallholder farmers: they exploit the ability of legumes to capture atmospheric nitrogen (N) and make it available to crops, permit growing trees in association with crops in space or time to benefit from complementarity in resource use and address most of the biophysical and socio-economic limitations identified with the earlier technologies based on using N-fixing tree legumes, such as green manures (Akinnifesi et al. 2010a; Sileshi et al. 2014). Fertilizer trees can be managed in alley cropping, intercropping, relay cropping and improved fallow as well as in traditional agroforestry parklands. The biomass they produce can be used ether in situ or in biomass transfer systems. As such, these trees play a key role in the diversification of agroecosystems and increasing the fertility and productivity of land. As they add large nutrient inputs to the soil, they can make a major contribution to sustainable agriculture by minimizing external inputs, particularly N fertilizers. Fertilizer trees have an added advantage, ensuring a multifunctional agriculture that provides timber, fodder, shade, soil improvement, carbon sequestration, watershed management and resilience to climate change (Luedeling and Neufeldt 2012; Sileshi et al. 2014). For example, leguminous trees and shrubs improve soil fertility through enhanced nutrient availability and nitrogen supply through biological N fixation, organic matter build-up, recycling of N from depth and improved soil physical and biological conditions (Akinnifesi et al. 2006b).

Alley cropping is defined as the planting of hedgerows of trees at wide spacing, creating alleyways within which agricultural or horticultural crops are produced (Kang et al. 1990). Alley cropping is synonymous with hedgerow intercropping. It is one of the common temperate agroforestry practices in South America, North America (USA and Canada), Europe, Asia and Africa (Oelbermann et al. 2004). In tropical Africa, it was developed as one of the alternatives to slash-and-burn agriculture (Kang et al. 1990; Kang 1993). Early work on alley cropping compiled by Kang et al. (1998) indicated that a large body of literature has been published on alley farming research and development in Africa. In the humid and subhumid tropics, alley cropping involves growing maize, beans or cassava between rows of perennial woody legumes of the genera *Albizia*, *Calliandra*, *Flemingia*, *Inga*, *Gliricidia*, *Leucaena*, *Senegalia* and *Vachellia*. The woody species may be regularly coppiced (Kang et al. 1999). Coppiced trees are periodically pruned, and their biomass is applied either as mulch or incorporated into the soil to improve soil fertility. Pruning reduces shading and below-ground competition with companion crops, besides providing N-rich mulch and green manure to maintain soil fertility and enhance crop production and provide protein-rich fodder for livestock. Results of on-station and on-farm trials have shown consistently that alley farming is efficient in reducing soil erosion, improving soil organic matter and nutrient status and sustaining crop yields under continuous cropping (Adesina 1999). Maize production under alley cropping has also been found to be socially profitable and financially competitive when compared to maize production relying only on chemical fertilizer (Adesina 1999).

Intercropping of fertilizer trees with cereal crops is an improvement building on the characteristics and advantages of alley cropping, but minimizing the biophysical limitations, such as "hedge effect", competition and tree management (Akinnifesi et al. 2006b, 2010a). In intercropping, fertilizer trees are managed by means of periodic pruning. The best-known example is *Gliricidia*—maize intercropping in southern Africa (Sileshi et al. 2012). Once planted, the trees are continually managed to supply green manure on the same piece of land. Fertilizer trees flourished in southern Africa because most of the potential constraints to the adoption of alley cropping, especially socio-economic factors, such as insecure land tenure, high labour costs for tree pruning as well as the area of land lost to trees (Adesina et al. 2000) were overcome in redesigned fertilizer tree systems, such as intercropping, relay and sequential fallows. Other technical issues overcome include tree management, choice of species and lack of adequate planting material and below- and above-ground competition between trees and crops. These have been variously documented in the reviews on fertilizer tree systems (Akinnifesi et al. 2010a; Sileshi et al. 2014). For instance, Akinnifesi et al. (2006b) showed scarcity of land, relatively low cost of labour and the high cost of mineral fertilizer improved the prospect for wide adoption of fertilizer trees in Malawi, with slight differences in uptake of different practices between regions. While *Gliricidia* intercropping and relay cropping are embraced in southern Malawi, the sequential fallow seemed to be preferred in northern Malawi and eastern Zambia (Akinnifesi et al. 2006b).

In relay intercropping, fast-growing nitrogen-fixing woody legumes are planted in a crop field at a time when annual crops such as maize have already been well established, usually within 2–4 weeks of crop sowing (Akinnifesi et al. 2010a). The legumes continue to grow after the crop harvest throughout the off-season. The tree-crop components only overlap for part of the growing season. Species such as pigeon pea and *Tephrosia* are recommended. As farmers prepare land for the next season, they clear-cut the legume and incorporate the biomass into the soil. Although the yield levels are usually lower than those of intercropping and improved fallows, relay intercropping works well on small farms, and the benefit of trees can be seen immediately after one season of tree growth (Akinnifesi et al. 2010a).

Biomass transfer is essentially moving green leaves and twigs of fertilizer trees from one location to another to be used as green manure (Kuntashula et al. 2004). This system is also known as "cut and carry system" (Ruhigwa et al. 1994). It has been demonstrated to be highly profitable in the production of high-value crops, especially vegetables, such as cabbage, rape, onion, garlic and tomato (Kuntashula et al. 2004, 2006).

Agroforestry parklands involve large canopy trees that are widely spaced in croplands (Boffa 1999). Parklands are the most widespread traditional land use system in Africa (Nair 1993) and the most extensive farming system (on a land area basis) found in the tropics (Boffa 1999). Agroforestry parklands are dominant in the savanna and Sahel biomes, where they provide socio-economic and ecological benefits (Dewees et al. 2011; Bayala et al. 2014b). In Mali, for example, agroforestry parklands occupy about ninety percent of the agricultural land (Kalinganire et al. 2007). Trees in agroforestry parklands are left following clearance of land for agriculture or they spontaneously germinate from dispersed seeds. The most common fertilizer tree in agroforestry parklands is *Faidherbia albida*. Reverse phenology in *F. albida*, which sheds leaves during the rainy season and is in leaf during the dry season (Roupsard et al. 1999), is responsible for a substantial increase of grain yield under its canopy (Bayala et al. 2012).

4.2.2 Fodder Tree Systems

Fodder tree systems involve protein (fodder) bank and silvopastoral management (Chakeredza et al. 2007). Protein banks are stands of trees or shrubs established within a farm or pasture area to serve as a supplementary source of protein-rich fodder for livestock (Sileshi et al. 2014). They also bridge forage scarcity associated with the dry season. In the wet season, livestock graze on grass and herbaceous plants in pastures and woodlands. The quantity and quality of this forage normally decline in the dry season. To maintain animal health and avert loss of productivity, farmers supplement dry season forage with concentrates or fodder from trees and shrubs (Paterson et al. 1998; Bayala et al. 2014a). The latter has been shown to be economical in Kenya (Paterson et al. 1998). Forage is harvested by pruning the top and branches of fodder trees such as *Gliricidia*, *Calliandra* or various species of *Leucaena*, *Pterocarpus* and others that are grown in blocks on farmland. Livestock can also be allowed to graze directly on protein banks, but this can result in damage to the plants and wastage of fodder (Sumberg 2002; Hamer et al. 2007; Bayala et al. 2014a). Protein banks may also conserve soil on slopes, and if planted in strips along the contour they may serve as biological soil conservation measures.

Silvopastoral systems are defined as a land use system in which trees are integral parts of pastures, rangelands or other grazing systems (Sileshi et al. 2014). Silvopastoral systems are common in semi-arid areas, where they are used to overcome forage scarcity. In grazing systems, animals move freely and graze under trees scattered on pasture land. The trees provide shelter and shade for livestock and herdsmen and protect the animals from strong wind, and their branches can be lopped to provide pods (e.g. from *F. albida*) and twigs (e.g. from the African locust bean—*Parkia biglobosa* to feed livestock during the dry season (Teklehaimanot 2004). Provision of shade and fodder improves animal welfare and productivity. The livestock, in turn, are used to plough and provide manure to maintain crop productivity and milk and meat for human consumption. The trees in grazing systems can also be managed to provide timber and other wood and non-wood products for the farmers (Boffa 1999; Dewees et al. 2011).

In communal grazing land, overgrazing results in land degradation and low productivity. It causes the natural vegetation to disappear, and the resultant land with scant vegetation cannot support livestock, leading to conflict over resources. Rehabilitation of such land often involves exclusion of livestock by creation of exclosures (Mekuria et al. 2007) or enclosures (Nyberg et al. 2015; Wairore et al. 2016). These measures allow native vegetation to regenerate, providing fodder and wood, reducing soil erosion and increasing water infiltration (Mekuria et al. 2007, 2011; Wairore et al. 2016). The concept of rehabilitation of degraded lands by establishment of enclosures and agroforestry has been used successfully in West Pokot in Kenya. Establishment of living fences and intensive agroforestry within formerly degraded lands in West Pokot has increased vegetation cover, improved soil health and increased food production in the area (Wairore et al. 2016). Establishment of enclosures and agroforestry alleviated pasture scarcity and allowed the local Pokot pastoral community to participate in crop production (Wairore et al. 2016).

4.2.3 Fruit and Medicinal Trees

Fruit and medicinal trees play a significant role in the food, nutrition, health and income of millions of people in SSA (Akinnifesi et al. 2007; Jamnadass et al. 2011; Leakey and Akinnifesi 2017). Fruit- and nut-bearing trees are an important source of food, nutrition and income besides their potential to mitigate greenhouse gas emissions. Trees are usually planted and managed around homesteads and on farmland (as perennial crop orchards, semi-managed orchards with annual crops or dispersed trees in crop fields). The most prominent fruit trees in SSA include *Vitellaria paradoxa* (shea tree) in West Africa, *Mangifera indica* (mango) in East Africa and baobab in southern Africa (Rao et al. 1998; Teklehaimanot 2004). Many indigenous fruit tree species of Africa also produce edible fruits and nuts during the hunger period. Growth, fruit size, appearance and total yield of indigenous species can be improved through domestication (Akinnifesi et al. 2006a; Ofori et al. 2014; Leakey and Akinnifesi 2017).

Homegardens refer to a land use close to the homestead involving a mix of annual crops and perennial crops in combination with trees and sometimes in association with domestic animals. Homegardens have evolved through generations of gradual intensification of cropping in response to increasing human population and decreasing arable land (Kumar and Nair 2004). A review of the global distribution of homegardens suggests that people traditionally use trees in their homesteads to meet their needs of food, energy, shelter and medicines (Kumar and Nair 2006). Even though homegardens are highly heterogeneous, food plants (food crops and fruit trees) are the most common species in most homegardens throughout the world (Kumar and Nair 2004), suggesting that food and nutritional security is the primary role of homegardens (Kumar and Nair 2006). In homegardens, trees, shrubs, vegetables and other herbaceous plants are grown in dense and random arrangement (Whitney et al. 2018). Trees are also planted at specific locations to provide necessary shade or to avoid shading plants as appropriate (Kumar and Nair 2004) and to provide support for vines such as *Mondia whitei* (Hook.f.) Skeels and species of *Dioscorea* (yam). Akinnifesi et al. (2010b) showed that homegardens in Brazil help conserve biodiversity of native plant and animal species.

4.2.4 Fuelwood and Timber Trees

The demand for firewood, charcoal and timber has been rising and this is posing a serious threat to forests and diversity of some tree species in Africa (Santos et al. 2017). Advocacy for substitution of non-renewables with biomass-based materials will further increase the demand for wood. Fuelwood and timber trees can be planted in agroforestry arrangements, such as rotational woodlots, smallholder timber plantations, live fences and windbreaks. These practices provide integrated food-energy systems that maximize the synergies between wood and crop production. Regular pruning of the trees provides fuelwood for cooking and mulch or green manure for soil improvement. Production of timber and fuelwood on farms can reduce pressure on forests and woodlands and ease the task of fuelwood collection (Ndayambaje and Mohren 2011).

In the rotational woodlot system, food crops are intercropped with leguminous trees during the first 2–3 years. Then the trees are left to grow and harvested in about the fifth year, and food crops are replanted (Otsyina et al. 1996). Rotational woodlot systems utilize fast-growing tree species that can satisfy household and regional fuelwood demand while reducing harvesting pressure on local forests and the associated greenhouse gas emissions (Nyadzi et al. 2003; Kimaro et al. 2007). In Tanzania, species such as *Gliricidia sepium*, *Acacia crassicarpa*, *Acacia mangium*, *Acacia leptocarpa* and *Senegalia* (*Acacia*) *polyacantha* have been shown to produce large quantities of fuelwood (Nyadzi et al. 2003; Kimaro et al. 2007) and raise topsoil carbon above levels of 9–15 Mg C ha^{-1} obtained within 0–30 cm depth of fallowed miombo soils (Kimaro et al. 2007). The leaves and twigs, remaining after wood harvest, are usually applied as green manure to provide nutrients for the next crop (Nyadzi et al. 2003). By improving soil organic matter, rotational woodlots can increase post-fallow crop yield (Kimaro et al. 2007).

Live fences refer to lines of trees grown and used to delineate boundaries of farms or farm components, such as homesteads, crop fields, pasture plots and animal enclosures. Live fences are common among resource-poor farmers who lack cash to erect other types of fencing. When established with multipurpose trees, live fences can provide fuelwood, poles, timber, green manure or mulch, fodder and stakes for climbing beans. They can also stabilize the soil and control erosion. Trees in life fences are regularly pruned, pollarded or coppiced depending upon the species and type of product desired. For example, branches and twigs are pruned from live fences to provide fodder and fuelwood. Live fences are diverse in terms of species composition, although species with loose canopies are preferred, or dense canopies are pruned to minimize competition with crops (Ndayambaje and Mohren 2011). In East Africa, species, such as *Markhamia lutea*, *Grevillea robusta*, *Cupressus lusitanica*, *Euphorbia tirucalli* and *Erythrina abyssinica*, are established into hedges for wood production. In the Sahel, trees that provide fuelwood, e.g. *Ziziphus mauritiana* and *Balanites aegyptiaca*, are used together with other tree and shrub species to make live fences that protect crops against browsing animals (Kalinganire et al. 2007). Depending on the species planted, live fences also act as windbreaks (Kituyi et al. 2001; Ndayambaje and Mohren 2011). A windbreak is a row or multiple rows of trees or shrubs that block or redirect wind. Properly designed windbreaks can enhance and diversify income opportunities from timber production, modify microclimate and create refugia.

4.3 Agroforestry-Based Livelihood Options

There are four pathways through which agroforestry contributes to sustainable livelihoods: food production, health and nutrition, provision of wood-based energy and income generation. These pathways form agroforestry's basis for socio-economic and environmental development in SSA and are critical in shaping land use and management decisions in the region. Agroforestry contributes to household livelihood security by producing food and food additives, fuelwood, fibre, medicines, gums and resins, oils and fragrances and fodder for livestock. They also influence production of food from crops and livestock products, such as meat, milk and honey. These products can be directly used for home consumption or sold on the market to generate income. With income, it is possible to meet expenses related to other aspects of livelihood security, for example, housing, education, sanitation and even social integration.

4.3.1 Food Production

Agroforestry enhances food and nutritional security by supporting crop production and through provision of edible tree and livestock products (Dewees et al. 2011; Jamnadass et al. 2013; Franzel et al. 2014).

4.3.1.1 Cereal Productivity

Trees improve growth and yield of crops when the appropriate species are planted in optimum densities and appropriate pruning regimes are applied (Bayala et al. 2002, 2015). According to recent meta-analyses (Kuyah et al. 2019), average yields of staple crops were almost twice as high in agroforestry compared to yields in treeless systems. Agroforestry practices with the highest increase in crop yield are those that improve soil fertility: alley cropping, biomass transfer and planted fallow (Fig. 4.1).

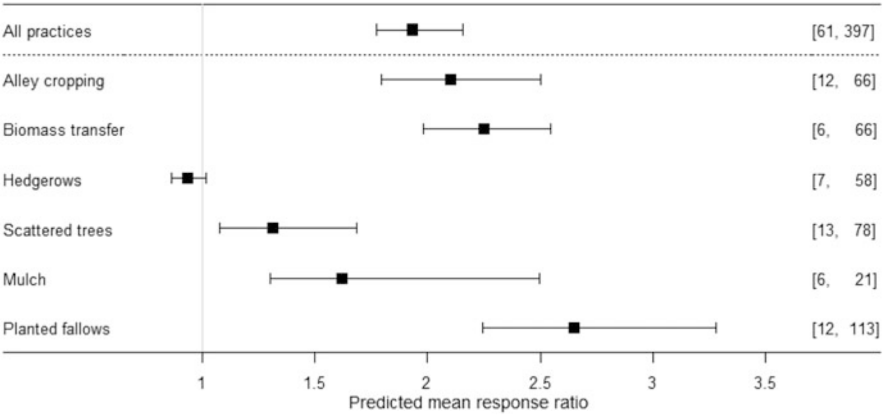

Fig. 4.1 Effects of different agroforestry practices on crop yield. Error bars represent 95% confidence interval (CI). Numbers in parentheses indicate the number of papers reviewed and the number of observations, respectively. Effects are significantly different from 0, if the 95% CI does not include 1 (grey line). Adapted from Kuyah et al. (2019)

There is an abundance of literature on how trees improve soil fertility, e.g. by increasing nutrient inputs through organic matter and nitrogen fixation or by reducing the loss of organic matter and nutrients through erosion control and promotion of nutrient recycling (Rao et al. 1998; Bayala et al. 2006; Akinnifesi et al. 2010a; Sileshi et al. 2014). Trees and shrubs that are used to improve soil fertility on degraded lands are those that can grow on poor soils and build up large amounts of biomass. There is evidence that trees improve crop yield on relatively fertile soils with enough rainfall, but tend to compete with crops when moisture is limiting and soils are inherently infertile, thus requiring appropriate management to minimize trade-offs (Cooper et al. 1996; Rao et al. 1998; Bayala et al. 2002, 2015).

Agroforestry practices, such as fertilizer tree systems, can increase cereal yields and reduce risks of crop failure by increasing soil fertility, improving microclimate and soil moisture (Bayala et al. 2012; Sileshi 2016) and reducing pest problems (Pumariño et al. 2015). One of the benefits of these practices is their ability to diversify the production system and reduce the risks especially for less resource-endowed and vulnerable households. According to Kamanga et al. (2010), maize intercropped with pigeon pea or *Tephrosia* was less risky for resource-poor farmers compared to fully fertilized maize, which had acceptable risk only for resource-endowed farmers in central Malawi. Maize intercropped with pigeon pea was found to be the least risky technology for all resource groups (Kamanga et al. 2010). Similarly, Sirrine et al. (2010) found that the most vulnerable households in southern Malawi were better off intercropping 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.

4.3.1.2 Fruits and Vegetables

Fruits and vegetables common in homegardens provide food security because they mature at various periods throughout the year. Some trees found in agroforestry parklands [e.g. the African locust bean, the shea tree, the tamarind (*Tamarindus indica*) and the baobab—*Adansonia digitata* (Kalinganire et al. 2007; Kehlenbeck et al. 2013; Gebauer et al. 2016)], in homegardens [e.g. the bush mango (*Irvingia gabonensis*) or njangsa (*Ricinodendron heudelotii*) (Dewees et al. 2011; Kehlenbeck et al. 2013)] and shrubs used in improved fallows [e.g. pigeon pea (Jamnadass et al. 2013)] produce edible seeds, fruits, nuts, kernels, leaves and oils. These are consumed fresh or cooked or processed into juice, cakes and other products, such as chutney, curries, pickles and sauce (Kalinganire et al. 2007). By diversifying food sources, agroforestry protects poor households during stress conditions, such as drought and preharvest periods, when staples are in short supply. Trees survive adverse weather conditions that often result in crop failure for most staple crops and, therefore, can provide food in cases of shortage, following crop failure. They also vary in phenology, meaning they can be harvested at different times of the year. For example, a fruit tree "portfolio" based on nine indigenous species in Malawi showed that at least one species was ripe every month (Akinnifesi et al. 2004; Jamnadass et al. 2013). Thus, by growing a collection of exotic and indigenous fruit species, households can access year-round fruit supply (Jamnadass et al. 2013; Kehlenbeck et al. 2013). Income from the sale of tree products can also be used to buy food.

4.3.2 Health and Nutrition

Contrary to the dietary simplification associated with conventional agricultural intensification with cereals (Fanzo et al. 2013), agroforestry can diversify diets by increasing the variety of available foods (Jamnadass et al. 2013; Kehlenbeck et al. 2013). Empirical evidence shows that dietary diversity increases with tree cover (Ickowitz et al. 2014). This suggests that the number of food groups consumed in a day could be increased by increasing the number and diversity of fruit trees and vegetables on farms. A diversified diet contributes to health and nutrition in several ways.

First, fruits, nuts, kernels, oils, condiments, vegetables and medicinal and aromatic plants are a major source of dietary minerals that ensure nutritional security (Kalinganire et al. 2007; Kehlenbeck et al. 2013). Some of these products have higher micronutrient, vitamin, fibre and protein contents than staple crops (Whitney et al. 2017). For example, ~ 50% of vitamin C needs of an adult human in Malawi can be met by daily consumption of 100 g of fruit pulp of either *Azanza garckeana* or *Strychnos cocculoides* available from November to March and 25 g of baobab fruit pulp from March to September (Jamnadass et al. 2013). Nutritional security alleviates deficiencies such as iron and vitamin A that are prevalent in most parts of SSA (Fanzo et al. 2013). With an appropriate portfolio of tree species, households can, therefore, access a year-round supply of vitamin-rich fruits and vegetables.

Many communities used to collect fruits and other edible tree products from forests and woodlands, which have become degraded or which are protected, so they are no longer (legally) accessible. Agroforestry allows the communities to access these products through domestication of indigenous shrub and tree species (Akinnifesi et al. 2007; Ofori et al. 2014). Priority indigenous food trees identified for domestication in SSA include *Allanblackia* spp., baobab, tamarind, bush mango, *Ziziphus mauritiana*, *B. aegyptiaca*, *Sclerocarya birrea* (marula), *Dacryodes edulis*, *Chrysophyllum albidum* and *Uapaca kirkiana* (Akinnifesi et al. 2007; Ofori et al. 2014). Having such a range of trees on farms can increase the range of edible tree products available for households in SSA, where low fruit and vegetable consumption is the main cause of micronutrient deficiencies (Ruel et al. 2005). Domestication can also provide fodder to support dairy and meat production in silvopastoral and agrosilvopastoral systems (Ofori et al. 2014).

Second, agroforestry contributes to health and nutrition by providing fodder and shade or shelter that improves the welfare and productivity of livestock. The livestock, in turn, provide milk, meat and eggs for human consumption. These are important sources of proteins, fats, vitamins and minerals, such as zinc, iron, selenium, calcium and phosphorus (Fanzo et al. 2013), given the dominance of carbohydrate-rich foods in diets of some households in Africa (Ruel et al. 2005). In East Africa, trees and shrubs scattered on farms, in hedgerows and on erosion control structures contribute substantial amounts of high-value fodder for livestock during the dry season (Angima et al. 2002; Kinama et al. 2007; Mutegi et al. 2008; Gachuiri et al. 2017). The fodder supplements grass forage, and some species (e.g. *Calliandra calothyrsus*) can be used as substitutes of commercial feeds (Franzel et al. 2014). In the Sahel and in drylands of Ethiopia, leaves, twigs and pods are lopped from *F. albida* in parkland agroforestry to provide fodder when other sources of forage are not available (Bayala et al. 2014a).

Third, trees and leafy vegetables, with medicinal value, contribute to the health of the people. This can directly provide cure and healing for some sicknesses, reducing the cost of healthcare. Some poor communities in Africa depend on medicinal plants for their primary healthcare. They cook parts of plants, such as roots, bark and leaves, and serve them with regular meals or prepare pastes and concoctions. The latter can be taken in dried form or applied externally to the hurting part of the body. A survey of priority functions of agroforestry parkland trees and shrubs in Burkina Faso, Mali, Niger and Senegal found that nearly all 116 species listed by 425 informants in 45 villages provide food (90%) and medicines (93% of the species) in addition to other benefits (Faye et al. 2011). A variety of trees and shrubs have been documented as serving as both food and medicine (Kalinganire et al. 2007; Jamnadass et al. 2011; Dimobe et al. 2018). For example, *R. heudelotii* found in homegardens is used to treat constipation, dysentery and eye infections; its kernels and seeds are also used in stews and the oil industry, respectively (Jamnadass et al.

2011). Income from sale of agroforestry tree products can contribute to meeting the cost of nutrition and household healthcare (Dimobe et al. 2018).

4.3.3 Wood-Based Energy

Production and use of fuelwood are important livelihood strategies in SSA where about 81% of the households (excluding South Africa) rely on wood fuel as their primary source of energy (World Bank 2011). The main fuelwood in SSA is charcoal and firewood. Charcoal is mainly used in urban areas while firewood is used by rural households for cooking and heating and in cottage industries for brickworks, tea processing and tobacco curing (Ramadhani et al. 2002; World Bank 2011; Iiyama et al. 2014). The demand for charcoal and firewood is projected to increase (Global Environment Fund 2013) in many countries in SSA, as they remain the most readily available sources of energy and the most affordable alternatives to kerosene, liquid petroleum gas and electricity (Iiyama et al. 2014). More fuelwood must, therefore, be produced on agricultural land if the fuelwood demand is to be met on a sustainable basis (Ndayambaje and Mohren 2011).

Approximately 20% of fuelwood in Africa is produced in agroforestry systems (Sharma et al. 2016). Agroforestry fuelwood production can provide more sustainable alternatives compared to forest and woodlands sources (Iiyama et al. 2014). For example, firewood from agroforestry is often harvested by selecting branches or collecting deadwood from trees. Woodlots are also sometimes established on farms for charcoal production. Having fuelwood in the farm is important for women and children, who are responsible for all tasks related to fuelwood collection for cooking in most SSA countries. The literal translation of a woman getting married (*okhutekha*) in the Luhya community in Western Kenya is "to cook". As this terminology suggests, women in the region devote a lot of time to gathering firewood and cooking while men may be involved in the production and sale of fuelwood. This situation is also observed in some countries, such as Burkina Faso, Togo and Benin in West Africa, indicating that in SSA, the collection of firewood by women and production or sale of fuelwood by men are common. In some parts of western Kenya, women spend about 2–5 hours per day collecting firewood (Bishop-Sambrook 2003). Reducing the time used to collect fuelwood can allow youth to allocate more of their time to their education and women to reallocate time to other activities.

Experimental studies and inventories of fuelwood across SSA report substantial amounts from various species under different agroforestry practices (Fig. 4.2a). The quantities produced vary with agroforestry practice and region, but are generally sufficient for meeting the fuelwood need of 486–500 kg per person per year for up to ten households of 3–7 people (Fig. 4.2b). This production is equivalent to the current 0.67–0.69 m^3 per capita per year (Ndayambaje and Mohren 2011; Iiyama et al. 2014). Exceptions are noted for hedgerow intercropping with *Daniellia oliveri* or *G. sepium* in Benin (Böhringer and Leihner 1996) and windbreaks with *Bauhinia rufescens*, *Acacia holosericea*, *F. albida* and *Vachellia nilotica* in Niger because of

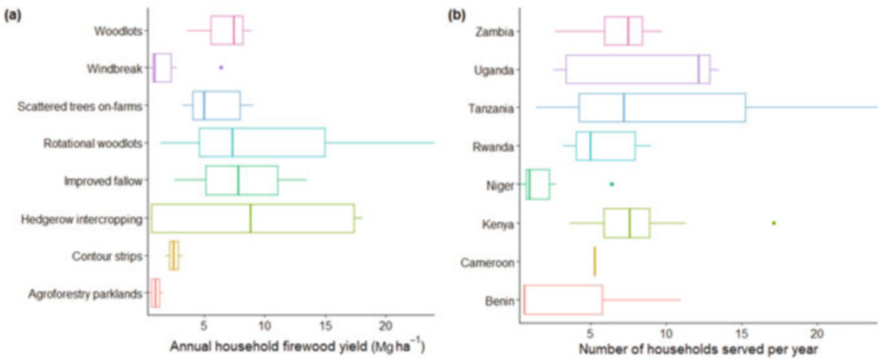

Fig. 4.2 Annual production of fuelwood from different agroforestry practices in sub-Saharan Africa (**a**) and the number of households served by fuelwood from agroforestry per year (**b**). Plot in (**a**) based on means reported for the agroforestry practices in Lulandala and Hall (1987), Jama and Getahun (1991), Kwesiga and Coe (1994), Lamers et al. (1994), Böhringer and Leihner (1996), Nyadzi et al. (2003), Siriri and Raussen (2003), Harmand et al. (2004), Kimaro et al. (2007), Jama et al. (2008), Avohou et al. (2011) and Ndayambaje and Mohren (2011)

larger household sizes with an average of 7.1 persons (United Nations 2017) and low amounts of fuelwood produced (Lamers et al. 1994).

Even though almost all agroforestry practices can provide fuelwood, the main fuelwood production technology in agroforestry is rotational woodlots. These are found to be the most promising agroforestry practice for fuelwood production in semi-arid areas (Ramadhani et al. 2002; Nyadzi et al. 2003; Kimaro et al. 2007). When used with fast-growing nitrogen-fixing species, they allow intercropping without compromising crop yield in the first 2 years. They produce large amounts of wood for charcoal and twigs for livestock after 5 years and improve crop yield after the wood harvest (Nyadzi et al. 2003; Kimaro et al. 2007). In Tanzania, wood productivity in rotational woodlots was about three times higher than that of local miombo woodland vegetation and was sufficient to meet household firewood demands for 7–16 years (Kimaro et al. 2007). However, adoption of rotational woodlots is low (Nyadzi et al. 2003) as farmers instead prefer planting trees for commercial timber or maintaining a diversity of species for multiple benefits. For example, in Rwanda, western Kenya and Ethiopia, farmers often maintain small monospecific woodlots of eucalypts or other fast-growing species, which supply fuelwood and utility poles or timber (Kituyi et al. 2001; Ndayambaje and Mohren 2011). The woodlots are found at homesteads and on slopes (normally highly degraded land) in Rwanda and Kenya or as communal hillside plantations in Ethiopia.

Firewood production has also been reported in agroforestry systems whose primary objective is to improve soil fertility, such as improved fallows and hedgerow intercropping (Jama and Getahun 1991; Siriri and Raussen 2003; Jama et al. 2008), and multipurpose agroforestry systems, such as agroforestry parklands (Boffa 2015). Fertilizer trees grown in relay intercropping can also produce substantial amounts of fuelwood. For example, over 90% of the domestic fuelwood needs were met from a hectare of 2–3-year-old *Sesbania* trees in Malawi (Kamanga et al. 1999). Pigeon pea production has also been successfully integrated with energy-saving stoves, and this has reduced the frequency of buying and collecting fuelwood in parts of Malawi (Orr et al. 2015). Fuelwood is also reported as a priority use of on-farm trees in many surveys on farm agrobiodiversity or livelihood benefits of trees (Tabuti 2012; Reppin et al. 2019).

4.3.4 Income

Agroforestry supplements household income through sale of surplus staples or vegetables, livestock or livestock products and trees and tree products. Salable tree products include fruit, nuts, kernels, edible leaves, oils, condiments, gums, resins, building poles, stakes for climbing beans, timber, fuelwood, fodder and medicines (Kalinganire et al. 2007; Dewees et al. 2011; Place et al. 2016). Some of these products and services such as improvement of soil fertility substitute what farmers would otherwise have to buy.

Using national household surveys, Miller et al. (2017) found that more than 30% of all rural households in SSA cultivate trees on their farms and that these trees account 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. In Burkina Faso, Mali and Senegal, close to 50% of households obtained income from agroforestry, with fuelwood, fodder and fruits contributing between 10 and 24% of the total household income (Binam et al. 2015). In these countries, tree products were second only to crop production in terms of income generation (Binam et al. 2015). A study in Maradi, Niger found that adopters of farmer-managed natural regeneration (FMNR) had around 30% more income than corresponding non-adopters (Haglund et al. 2011). In another study in the same region, Rinaudo (2012) found an increase in household income by at least 140 USD per year. In West Pokot, Kenya, income from agroforestry products ranked fourth in total household income (Wairore et al. 2016). Opportunities for agroforestry to contribute to household income are projected to increase with population growth and economic development in SSA (Dewees et al. 2011).

4.3.4.1 Income from Non-wood Products

Non-wood tree products provide regular income to farmers. The value of these products varies considerably by species and region. Most species maintained by farmers in agroforestry parklands are preferred because of their income-generating values (Place et al. 2016). For example, fruits and leaves of baobab (Pye-Smith 2013), cakes processed from fruits of *Detarium microcarpum*, seeds of the African locust bean, fruit pulp of tamarind and *Z. mauritiana* and the nuts of shea tree generate substantial income for households in West Africa (Teklehaimanot 2004;

Kalinganire et al. 2007; Pye-Smith 2013; Binam et al. 2015). Mangoes (the third largest group of fruits produced in SSA, after bananas and citrus fruits) provide a major source of income for smallholders. A survey of 121 households in six villages in Mangwende, Zimbabwe, found that 82% of the households had one or more mango trees, most of which were planted in homegardens and around the homesteads (compounds); 94% of the households sold mangoes from their farms (Musvoto and Campbell 1995). In Hoima, Uganda, farmers intercropping fruit trees with food crops earned enough income to meet household needs (Recha et al. 2017). Gum from *Senegalia senegal* contributed significantly to incomes in Sudan (Aymeric et al. 2014), similar to marula in southern Africa (Shackleton and Shackleton 2004).

Agroforestry also provides opportunities for households to generate income through processing and value addition for tree products and establishment of tree nurseries (Asaah et al. 2011). Value addition allows farmers to obtain high prices, for example, from shea nuts, cashew, mangoes, gum and resins (Place et al. 2016). Shea butter is both sold at both local markets and exported for use in the chocolate, cosmetics and pharmaceutical industries within Africa and in Europe (Kalinganire et al. 2007; Place et al. 2016). Post-harvest processing of shea nuts yields greater returns than sale of raw shea nuts and provides large quantities of husks and cakes that are used as compost and fuel (Boffa 2015). Fruits and nuts from *B. aegyptiaca* can be processed into oils (Pye-Smith 2013). Processing and value addition can increase availability of tree products throughout the year, creating opportunities for new markets and off-farm employment.

4.3.4.2 Income from Fodder Trees

Silvipastoral and agrosilvopastoral systems produce livestock and livestock products (e.g. milk, meat and manure) that can be sold for cash. Increasing livestock densities have raised the demand for fodder in SSA, especially during the dry season when grass forage is scarce. Fodder from trees is rich in proteins, vitamins and minerals like calcium. It can help to bridge times of forage scarcity, increase milk production and can be used to substitute dairy meal (Place et al. 2009; Paterson et al. 1998). For example, milk production can be increased between 0.6 and 1.3 kg per day by feeding animals an additional 2 kg of *C. calothyrsus* (Place et al. 2009). Farmers can also earn income from the sale of fodder or seeds of fodder trees (Paterson et al. 1998; Place et al. 2009; Ayantunde et al. 2014; Bayala et al. 2014a). Analysis of economic impacts of fodder shrubs in East Africa projected a net income between USD 101 and 122 per year from 500 bushes of *C. calothyrsus* after 2 years (Place et al. 2009). In the Sahel, the price of browse (*Combretum micranthum*, *Piliostigma reticulatum*, *Pterocarpus erinaceus* and pods of *F. albida*) has been estimated to evolve from 95 FCFA F in November to 298 FCFA F in January (1 USD = 500 F CFA) (Ayantunde et al. 2014).

4.3.4.3 Income from Wood Products

Farm production of wood, including timber and poles, for local markets is increasing in Africa (Place et al. 2016; Sharma et al. 2016), making significant contributions to improving rural livelihoods through income generation (Kiplagat et al. 2011). In Kenya, much of the timber from farms is produced in woodlots (e.g. *Eucalyptus* spp. or *Vachellia* spp. in western Kenya and *Melia volkensii* in eastern Kenya) or along boundaries (e.g. *G. robusta* in central Kenya) (Kiplagat et al. 2011; Place et al. 2016). Trees in woodlots are often selectively harvested and sold. Agroforestry systems that include high-value trees (e.g. *G. robusta* in perennial tree crops such as coffee and tea or shea trees in cereals in agroforestry parklands) provide incomes when harvested. Timber species common in pasture, windbreaks and homegardens provide cash when the trees are cut and sold.

Charcoal and firewood provide income to a wide range of beneficiaries along the value chain, including people who harvest trees, produce charcoal, collect charcoal or firewood or transport or retail the commodity (Iiyama et al. 2014). Farmers practicing FMNR in four West African countries obtained higher income from sales of firewood (Pye-Smith 2013). In Niger, wood collected at the roadside and from farms contributed between USD224 and US 256 per household per year (Pye-Smith 2013). In West Pokot, sale of wood products from agroforestry, including firewood, ranked fourth in importance among all sources of household income (Wairore et al. 2016). In Tanzania, the net present value of rotational woodlots was 6.3 times higher than that of maize-fallow (Ramadhani et al. 2002). Species used to control soil erosion on slopes and to improve soil fertility via planted fallows also provide firewood that can be sold.

4.3.4.4 Income from Increased Crop Production

Economic studies of farm returns to land and labour [net present values (NPV) and benefit cost ratios (BCR)] indicate that fertilizer trees are either comparable or better than inorganic fertilizer (Ajayi et al. 2009; Kamanga et al. 2010). In central Malawi intercropping maize with pigeon pea had consistently positive returns across the farmer resource groups, indicating its suitability to a wide range of environments and for the poorer farmers (Kamanga et al. 2010). Over a five-year cycle, the discounted net benefit of maize grown with species of *Gliricidia* (USD 327 per ha), *Sesbania* (USD 309 per ha) and *Tephrosia* (USD 233 per ha) compared favourably with maize grown with the recommended inorganic fertilizer (USD 349 per ha) in eastern Zambia. In eastern Zambia, fertilizer trees generated better returns per investment (BCR: 2.8–3.1) than with the recommended fertilizer purchased at market price (BCR, 1.8) or with the 50% government subsidy for fertilizer (BCR, 2.6) (Ajayi et al. 2009).

Franzel (2004) assessed the financial returns to farmers of three agroforestry practices, namely, fodder shrubs in Kenya, rotational woodlots in Tanzania and improved fallows in Zambia. He found that full adopters of these practices earned USD 68–212 per year more from these practices than from alternative available practices. Some studies (Phiri et al. 2004; Quinion et al. 2010) also indicated that farmers who take up the improved fallows in Zambia and Malawi have higher welfare, measured in terms of outcome parameters, such as increased asset base, among others.

4.4 Case Studies

4.4.1 Ex Ante Impact Analysis of Fruit Trees in Southern Africa

Many rural households rely on indigenous fruit trees as sources of cash and subsistence in southern Africa. Until the late 1980s, there was little effort to cultivate, improve or add value to these fruits. In 1989, the International Centre for Research in Agroforestry (ICRAF: now the World Agroforestry) initiated research-and-development work on indigenous fruit trees in southern and western Africa (Akinnifesi et al. 2006a). Studies suggest that the cultivation of wild fruit trees will become more important as rural households move from subsistence to a cash-oriented economy. During the season of food abundance, the collection, utilization and commercialization of indigenous fruits become important for household income portfolio diversification.

In southern Africa, several studies were conducted concerning the contribution of miombo fruits to the livelihood portfolio of the rural communities. Mithöfer et al. (2006) quantified the contribution of indigenous fruit trees towards reduction of vulnerability to food insecurity and poverty, using a multiperiod stochastic household income model. The results show that rural households in Zimbabwe are highly vulnerable to seasonal fluctuations in income, thereby identifying a critical period where households run high risk of being food insecure. The report recommended diversified season-specific income-generating portfolios of which indigenous fruit trees have an important role to play. The probability of rural households falling below the poverty threshold is at 70% during the critical food-insecure season during growing season of food crops, if no indigenous fruits are available, and this reduces at harvesting time. If indigenous fruit area available, the vulnerability can be reduced by about 30% during the critical period. This suggests that indigenous fruit trees can serve as an important risk-coping strategy, which can be further complemented by other livelihood strategies during the agricultural off-season and, thus, provide a cushioning effect to annually occurring poverty and hunger (Mithöfer et al. 2006).

An ex ante impact analysis in Zimbabwe showed that household consumption of indigenous fruits represents 42% of a family's food intake during the fruiting seasons. In addition, the marketing of these fruits contributed substantially to household income, keeping families above the poverty line during critical hunger periods (Mithöfer 2005). A household food security survey conducted in 2002 showed that an estimated 60–85% of all rural households in Malawi, Zambia and Mozambique lack access to food for as much as 3–4 months per year, especially during December to February (Akinnifesi et al. 2004). During this critical hunger period, 26–50% of the respondents relied on indigenous fruits as a coping strategy (Akinnifesi et al. 2004). In South Africa, 30% of households were reported to have planted new trees in their homesteads as a coping mechanism for hunger periods (Akinnifesi et al. 2006a).

4.4.2 Vegetable Production Using Biomass Transfer

Vegetables are valuable as sources of vitamins and minerals in the largely maize-based diet of rural households, especially in eastern and southern Africa. Vegetables also have high market value and can help generate income throughout the year (Kuntashula et al. 2006; Tschirley et al. 2009). Smallholder vegetable production has become a fast-expanding enterprise due to the increasing demand from rapidly increasing urban populations. The vegetables are often produced in nutrition gardens, promoted by non-governmental and church organizations targeting the poor and the sick, especially HIV patients, with the aim of improving their standards of living through improved nutrition and income generation. Nutrition gardens are often located close to water sources wherever possible, and this often tends to be in wetlands. Vegetable production is restricted to the dry season, mainly due to the high incidence of vegetable pests, diseases and waterlogging (Kuntashula et al. 2006). Declining soil fertility is one of the major factors limiting smallholder vegetable production in the wetlands.

Biomass transfer using fertilizer tree species has been proposed as a more sustainable means for maintaining soil nutrient balances in vegetable-based production systems in the wetlands in southern Africa (Kuntashula et al. 2004, 2006). In that regard, two separate studies were carried out in Zambia to assess the agronomic and economic feasibility of biomass transfer. In the first study the biomass transfer using *Gliricidia* and *Leucaena* in the production of cabbage, onion and a subsequent maize crop during the dry season was evaluated on the fields of 43 farmers (Kuntashula et al. 2004). In that study biomass transfer recorded higher net incomes than the control and required lower cash inputs than fertilized crops. Net income derived from cabbage and onion grown using *Gliricidia* at 12 Mg ha^{-1} was comparable with that from fully fertilized cabbage (Kuntashula et al. 2004). There were also additional benefits from the maize crop planted after vegetable harvests. The *Gliricidia* biomass treatments produced maize grain yields as high as those from the fully fertilized treatments (Kuntashula et al. 2004). *Gliricidia* leafy biomass produced vegetable yields comparable with those obtained from chemical fertilizers (Kuntashula et al. 2006). For instance, the increase in yields of cabbages grown on soils amended with leafy biomass of *Gliricidia* ranged between 85 and 167% relative to no soil amendment (Kuntashula et al. 2006).

In Zimbabwe, Muchecheti and Madakadze (2016) determined biomass accumulation and nitrogen recovery rates of rape (*Brassica napus*) as influenced by different legume tree pruning and the effect of combining these pruning with inorganic N fertilizer. The authors found that the application of the different pruning and inorganic fertilizer, alone or combined, increased total biomass yields of rape relative to the control. The sole pruning of *Vachellia karroo* increased the total biomass yield of rape by 1.09 Mg ha^{-1} on dry matter basis relative to the yields of the non-fertilized plots. The corresponding increases in biomass yield of rape following soil amelioration with sole pruning of *C. calothyrsus*, *Senegalia angustissima* and *Leucaena leucocephala* were 2-, 3.2- and 7.5-fold, respectively. The total biomass increases over the control plots following supplementation of pruning with a quarter of the recommended inorganic N were 13.31, 9.49, 6.81 and 5.23 Mg ha^{-1} on dry matter basis for *L. leucocephala*, *S. angustissima*, *C. calothyrsus* and *V. karroo* each with quarter recommended N, respectively. Similarly, Makumba and Phiri (2008) reported that *G. sepium* and *Tephrosia candida* biomass increased cabbage yields by 7.48 and 12.60 Mg ha^{-1}, respectively.

The profitability of the leguminous leafy biomass depends on the synchrony between N released from the decomposing organic matter with the demand for N by the crop (Myers et al. 1994) as well as the structure of the inputs, especially the labour costs (Kuntashula et al. 2004). Kuntashula (2004) found that the structure of costs differed between the full fertilization and the leafy biomass applications. The biomass transfer technologies recorded higher net incomes than the control and required lower cash inputs than the fully fertilized crop. Net incomes of the biomass treatments were substantially reduced by the labour costs for pruning and incorporation of the biomass. This is an important implication for the African farmer since cash resources to obtain external inputs are the major impediments to production. In rural set-ups of most African countries, the opportunity cost of labour is very low because most of the family labour cannot find alternative payable jobs. This family labour can, therefore, be deployed in the use of leafy biomass without serious consequences of resource misallocation.

One of the key benefits of this practices is the improvement in soil fertility. Mafongoya and Jiri (2016) found high residual fertility terms of inorganic nitrogen (nitrate and ammonium) after harvesting vegetables, especially in plots treated with 12 Mg ha^{-1} of *Gliricidia* pruning. The high levels of nitrate after onion and cabbage harvest could lead to nitrate leaching during the rainy season if not utilized. Farmers grow maize crop after harvesting the vegetables (usually in September) using the residual soil fertility. The maize is harvested in the middle of the hunger period (December–January) in southern Africa. The sale of green maize is a good source of income and food security to farmers during this hunger period (Mafongoya and Jiri 2016). Measurements after maize harvest showed that the residual N in the soil was reduced to undetectable levels (Mafongoya and Jiri 2016). This shows that this cropping system can minimize the environmental problems associated with N leaching.

4.4.3 Cereal Production in Agroforestry Parklands

Using 64 observations from 15 studies conducted in Burkina Faso, Mali, Niger and Senegal, Bayala et al. (2012) found that parkland trees increase crop yield between 0.14 and 0.24 Mg ha^{-1} depending on tree species. The most limiting factor for the associated crops in parklands being light (Kater et al. 1992; Bayala et al. 2008; Bazié et al. 2012), yield increase magnitude can be enhanced through crown pruning for C_4 cereal crops (Kater et al. 1992; Bayala et al. 2002) or by using shade-tolerant crops (Bazié et al. 2012; Pouliot et al. 2012; Sidibé et al. 2017). Root pruning has also been tested but the associated increase in yield was less than the one due to crown pruning (Jones et al. 1998). These management actions are not needed for shrubs intercropped with cereals (Dossa et al. 2012) and some tree species like *F. albida* because of its atypical phenology (Roupsard et al. 1999; Kho et al. 2001).

As trees in parklands are not planted in most cases, a common way of renewing them is through FMNR, where farmers protect and nurture trees and shrubs that naturally grow on farms (Box 4.1). FMNR in Niger exemplifies successful application of agroforestry on degraded lands for improved livelihoods (Haglund et al. 2011; Binam et al. 2015; Place et al. 2016) in a country where tree plantation (forest) programs have low seedling survival rates, about 20%, and agricultural intensification had failed to improve food security and incomes (Pye-Smith 2013). The success of FMNR in Niger is attributed to preserving "the right tree in the right place", focusing on native species and involvement of local communities (Pye-Smith 2013). People willingly invested time, labour and available resources once they noticed significant impacts of trees on soil fertility, crop yield, wood supply, animal welfare, income and food security (Haglund et al. 2011; Binam et al. 2015; Place et al. 2016).

Box 4.1 Farmer-managed Natural Regeneration in Niger

Farmer-managed natural regeneration (FMNR) is a practice of actively managing and protecting non-planted trees and shrubs in order to increase the quality or quantity of woody vegetation on farmland. Whether such achievements materialize depends on the existence of living root systems or seeds in the soil. Farmers protect and manage trees that regenerate spontaneously on their farms, contrary to the usual practice where sprouts are slashed or burned down before each planting season. After emergence, farmers select the most vigorous stems of the sprouts, which they prune so that the stems grow into a straight trunk; the rest are culled. In 2005, 5 million hectares of treeless, highly degraded land in Maradi and Zinder had been transformed into green landscape through FMNR. FMNR added to the landscape more than 200 million new trees since 1985 and prevented further land degradation.

FMNR improved food security and incomes in Niger. In Zinder and Maradi, trees on farms increased crop yields by 15–30%. At the national scale, annual agricultural production on restored croplands increased by about 500,000 Mg. Crop yields improved significantly because of improved soil fertility and microclimate (reduced wind speed and decreased local temperatures). The trees also produce fruits and leaves for human consumption, fodder for livestock, fuelwood, traditional medicine and other products and services. Surplus from trees can be sold on the market allowing farmers to pay for household needs and buy food on the market in case crops fail. Farmers who adopt FMNR and practice it continuously can increase their gross income per month by around 72 USD per year. Multiple benefits of trees compensate for possible losses in cereals where tree density and canopy cover are high.

Co-benefits from FMNR include improved social well-being. Improved access to fuelwood and fodder reduces the daily workload for women. For

(continued)

Box 4.1 (continued)
example, the presence of trees on cropland reduced the time spent gathering firewood from 2.5 hours per day to an average of half an hour per day. High tree cover on the landscape can control wind speed, reduce airborne dust and have a cooling effect. The trees provide other environmental services, such as watershed protection and carbon sequestration. Provision of wood and fodder can reduce the pressure of firewood collection and livestock grazing in adjacent forests.

Further reading: Faye et al. (2011), Haglund et al. (2011), Bayala et al. (2012), Luedeling and Neufeldt (2012), Binam et al. (2015) and Gray et al. (2016).

Insights from FMNR in Niger have been replicated and scaled up across Africa, where agroforestry has transformed degraded lands into fertile farmlands by increasing on-farm tree densities, for example, in Mali (500,000 hectares), Ethiopia (1 million ha), Burkina Faso, Malawi and Senegal (Gray et al. 2016). Farmers in these countries have benefited through higher crop yields, increased provision of fodder, firewood and other tree products, income from sale of these products, surplus staples and employment (Gray et al. 2016).

4.4.4 Fodder Banks

A review of work carried out in Tanzania, Malawi and Zimbabwe has provided substantial evidence for improvement in smallholder dairy production (Chakeredza et al. 2007). Data on the profitability of fodder shrubs in zero grazing, cut and carry systems are available from Tanzania, Kenya and Uganda. In Tanzania, Otsyina et al. (2001) calculated that by using either *Leucaena pallida*, *Leucaena collinsii* or *Leucaena diversifolia* as substitutes to dairy concentrate, a farmer could save about USD 310 per cow per year. In central Kenya, Franzel (2004) found that when *Calliandra* was used as a substitute to the basal diet, annual net returns increased by USD 142. Farmers who planted 500 *Calliandra* seedlings could increase their net income by 101–122 USD a year from the second year of planting onwards. By using *Calliandra* as a supplement (6 kg fresh leaves per day) to an existing basal diet (with 2 kg dairy meal), the calculations in East Africa show that a farmer's net income increases by USD 62–115 (Chakeredza et al. 2007). Fodder banks have also been experimented and introduced in farmers' fields in West Africa (Hamer et al. 2007; Bayala et al. 2014a).

4.5 Knowledge Gaps and Barriers

4.5.1 Knowledge Gaps

A gap in knowledge relates to a lack of holistic valuation of the benefits of agroforestry. So far, the evidence on livelihood benefits of agroforestry is scattered within primary studies. Published syntheses are limited to specific ecosystem services—especially certain provisioning ecosystem services and the role of agroforestry in supporting food production. This gap persists in the literature because researchers prioritize economic benefits or tools for measuring non-economic livelihood benefits are not well developed. Studies on livelihood benefits of agroforestry in SSA mainly focus on market benefits, such as crop yield, timber, fuelwood and non-wood tree products (Kuyah et al. 2016). Those studies that consider non-market benefits limit research to tree cover and associated agrobiodiversity. Non-market livelihood benefits of agroforestry are, therefore, undervalued or omitted altogether in many studies. However, livelihood security is not just linked to income, but to a much broader set of relationships, conditions and physical factors.

The cultural role of agroforestry or its products is often overlooked. A recent review identified an apparent lack of studies on cultural benefits of trees on farms in SSA (Kuyah et al. 2016), although some of the trees documented to provide cultural benefits in forests are also found on farms. Many tree species found on farms have a central place in peoples' traditions and ceremonies. For example, beer from marula is shared with neighbours, helping to build and maintain social networks (Shackleton and Shackleton 2004); shea butter is presented as a gift among women to celebrate marriage, births or dowries (Boffa 2015); homegardens provide fruits for sharing, and they also play a role in cultural festivals and religious activities. The majority of rural people traditionally use wild species for medicine and other purposes. Harvesting and processing medicinal plants, e.g. shea butter and other tree products, entail traditional knowledge passed on across generations. Understanding the contribution of trees to various aspects of livelihoods is needed to support informed decision-making and evidence-based land use management in SSA.

4.5.2 Overcoming Barriers

Beyond physical suitability, such as favourable sites, appropriate tree and crop germplasm and adoption of suitable land management practices (Cooper et al. 1996; Rao et al. 1998; Akinnifesi et al. 2007; Kalinganire et al. 2007), successful agroforestry systems require enabling conditions, such as governance, gender synergies, secured land tenure, investment, markets for agroforestry inputs and outputs (Mbow et al. 2014). This underscores the complex nature of factors that hinder the ability of agroforestry to provide livelihood security. They include political, social, cultural, economic and ecological factors. Barriers related to adoption of agroforestry have widely been documented. Nevertheless, there are barriers that directly relate to harnessing livelihood benefits from agroforestry. On the political front, policy frameworks in many countries determine the ownership and, thus, realization of monetary value from trees on farms.

Ecological factors include low productivity and suboptimal management. Agroforestry systems include many species that grow in different places. Suitability of some species has been evaluated and, in some situations, farmers are able to identify species that best match the conditions of the planting site and know where to get the seed for those species. However, many other species are yet to be domesticated, and information on the characteristics of each species, their management and productivity is lacking. Domestication of indigenous species can lead to productivity gains and preserve those species that are threatened by overharvesting. This requires knowledge on the reproductive biology of potential agroforestry species, the correct densities that are compatible with different crops and the kind of management required to sustain productivity gains. It is not clear how climate change will affect trees, since as plants they have specific environmental and climatic requirements. In some cases, lack of experience with trees, and lack of time and knowledge required for management can limit livelihood benefits derived from agroforestry. In other cases, there is need for awareness creation for agroforestry practices that produce high-value products. ICRAF and other partners have played a significant role creating awareness for agroforestry opportunities in Africa. There is rising interest on public-private partnership with a focus on making agroforestry profitable. The involvement of the private sector is likely to lead to development of value chain that is critically needed for many agroforestry practices.

Economic factors that limit harnessing livelihood benefits of agroforestry include limited capital for investment, long payback period and limited market opportunities for agroforestry products. Agroforestry requires investment in inputs (e.g. seedlings) and time. The many benefits (co-benefits, products and services) of agroforestry are often not realized until after some years. Delayed return on investment demotivates farmers to invest in agroforestry and, therefore, incentive schemes during the establishment years can be catalytic. Some of the current schemes focus on conservation of trees (in forests) in order to limit deforestation, which leaves out management of trees on farms. Another barrier is that markets and value chains for agroforestry products are generally underdeveloped.

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Agroforestry Systems for Arid Ecologies in India

5

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Abstract

The hot arid region is spread over 31.7 million hectare in India with major chunk located in the north western part (28.57 m ha) of the country. However, the maximum 61% area of the hot arid region is occupied by the western Rajasthan alone. Agriculture in the region is challenging task owing to low rainfall (100–-400 mm yr^{-1}) and high temperature (16 °C in winter and more than 34 °C in summer) and open pan evaporation (1800 mm yr^{-1}) as well, which make the region dry with aridity index 0.05–0.65. Under such conditions, crop cultivation becomes difficult, crop production is highly variable and economic viability of the system is poor. Agroforestry in such conditions, particularly *Prosopis cineraria*-based traditional system, has become the way of life as the tree has acclimatized there since generations and provides food, fodder, fuelwood, fruit and timber to the human and livestock population. Since trees in agroforestry systems have a deep tap root system and livestock particularly small ruminants survive well on browsing materials. These attributes together make agroforestry sustainable and climate smart in the hot arid region particularly more in the era of global warming. Besides, the *P. cineraria*-based traditional agroforestry, now several systems of agroforestry, have been developed to cater the need of ever-increasing population both of human and livestock in the region.

Keywords

Agroforestry · Components of agroforestry · Hot arid region · Improved agroforestry system · Perennial components · Traditional systems

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5.1 Introduction

The hot arid region of India receives rainfall as low as 100 to 400 mm yr^{-1}, but mean annual evapotranspiration is as high as 1800 mm yr^{-1}, which makes the region arid with aridity index of 0.05–0.65 (Safriel and Adeel 2005). Such dryland conditions occur in all parts of the world and cover an area of 6.1 billion hectares across the globe (FAO 2016). Drylands are sensitive to degradation (Reynolds et al. 2007) and principal processes of land degradation include erosion by water and wind, loss of soil fertility, salinization, fertility depletion, physical degradation and reduction in total and biomass carbon and decline in land biodiversity (Sivakumar 2007). Recent studies have indicated the need to restore drylands to cope with the effects of drought, desertification, land degradation and climate change. According to Davies et al. (2012), human population increase has led to steady expansion of cropping even on the most marginal drylands. Vegetation in arid regions is sparse which is comprised of perennial and annual grasses, other herbaceous plants, shrubs and small trees. Vegetation constitutes primary source of life support where animal husbandry being major vocation of people that depends entirely on natural vegetation. Further, inhospitable climate, too deep or too shallow soils with low moisture and poor fertility and deep underground water, which is often brackish or saline, coupled with intense biotic pressure permit only specialized plants, which are well adapted to these climatic, edaphic and biotic adversities and fluctuations.

Land users can respond to environmental stresses by improving their agricultural practices and livestock production, which may lead to reduced soil erosion, and salinization. Improved management practices can lead to high biological productivity and improved human well-being, besides providing political and economic stability (MA 2005). Agroforestry plays a significant role in enhancing the land productivity and improving livelihoods of farmers in arid and semi-arid regions due to high risk involved with arable farming, which affected by low and highly variable rainfall, low soil fertility, high evapotranspiration and high wind velocity. The number of tree species is very limited in arid zones and also, they are slow growing due to limitations of environmental conditions. Tree-based traditional cropping systems play an important role in production system in hot arid regions of India (Tewari et al. 2014; Dagar and Tewari 2017; Soni et al. 2016). The native people in arid zones have often developed the production systems to minimize the adverse effects of frequent drought, in which woody perennials have a very important role from productive as well as resource conservation.

5.2 Distribution of Arid Regions of India

The hot arid regions of India lie between 24° and 29° N latitude and 70° and 76° E longitude, covering an area of 31.70 million hectares and involving seven states: Rajasthan, Gujarat, Punjab, Haryana, Andhra Pradesh, Karnataka and Maharashtra. An area-wise break-up of hot arid regions is presented in Table 5.1. In total, 11.8% of the country is under a hot arid environment. The arid regions of Rajasthan,

Table 5.1 Distribution of arid regions in different states of India (Bhandari et al. 2014)

State(s)	Area (million hectares)	Percent of total
Rajasthan	19.61	61.00
Gujarat	06.22	19.60
Punjab and Haryana	02.73	09.00
Andhra Pradesh	02.15	07.00
Karnataka	00.86	03.00
Maharashtra	00.13	00.4
Total	31.70	–

Gujarat, Punjab and Haryana together constitute the Great Indian Desert, better known as the Thar Desert. As arid western Rajasthan accounts for 61% of hot arid region of the country, therefore it is considered principal hot arid region.

The Thar Desert extends over about 0.32 million km^2 forming about 10% of the total geographic area of India; ~ 60% of the desert lies in the State of Rajasthan and 20% in Gujarat (Krishnan 1977; Sharma and Mehra 2009). It is one of the smallest deserts of the world and has a wide variety of habitats and a high biodiversity. It is the most densely populated desert of the world. During summer, the maximum temperature generally varies between 40 and 45 °C, occasionally reaching 51 °C. During winter, minimum temperatures may fall to −2 °C at night. The true desert or *Marusthali* consists of Jaisalmer in its entirety, northern Barmer and the western parts of the Jodhpur, Bikaner and Churu districts (Sharma and Mehra 2009). Due to its unique location at a biological crossroads of the Indian subcontinent, the Thar Desert supports rich biodiversity. In the Thar, *Dicanthium-Lasiurus-Cenchrus* association is the most common (Dabadghao and Shankarnarayan 1973). Most of the other vegetation consists of stunted, thorny or prickly shrubs and perennial herbs which are resistant to drought. Sand dunes form 58% of the desert. Stabilized dunes are covered mainly by *Capparis decidua*, *Calotropis procera*, *Calligonum polygonoides*, *Acacia senegal*, *Prosopis cineraria*, *Aerva javanica*, *Aristida adscensionis* and other psammophytic species. There are several saline depressions in the Thar with characteristic halophytic vegetation.

The production and life support systems in this part of the hot Indian arid zone are constrained by climatic limitations including: low annual precipitation (100–300 mm), very high temperature during the summer season (mean maximum temperature 41 °C) touching a maximum of 48° to 50 °C, short (December to mid-February) cool and dry winters (the mean winter season temperature varies from 10° to 14 °C), high wind speed (30–40 km/hour), high evapotranspiration and general low humidity (an aridity index of 0.045–0.19) (Sharma and Tewari 2005).

Sand dunes are a dominant land formation of the region. More than 58% of the area is sandy and intensities of dunes vary from place to place. In general, soils contain 1.8–4.5% clay, 0.4–1.3% silt, 63.7–87.3% fine sand and 11.3–30.3% coarse sand. They are poor in organic matter (0.04–0.12%) and low to medium in phosphorus content (0.05–0.10%). The nitrogen content is mostly low, ranging between 0.20

and 0.07%, and infiltration rate is very high, at 7–15 cm hr^{-1} (Dhir 1997). Because of the complete absence of any aggregation, the soils are highly erodible.

5.3 Agroforestry Systems in hot Arid Regions of Rajasthan

Agroforestry is a sustainable land management system which involves woody components such as trees and shrubs along with agricultural crops including pasture/animals simultaneously or sequentially, on the same unit of land, and at same time to meet the ecological as well as socioeconomic needs of people. Agroforestry systems are helpful in maintaining soil productivity at optimum levels over a long period of time, when compared to agricultural crops alone, because the leguminous trees used in agroforestry systems fix nitrogen.

Crop productivity is enhanced due to improved soil fertility and ameliorative influence of shade by reducing understorey temperature and evapotranspiration under the tree canopy (Bunderson et al. 1990). The cropping system is more remunerative when incorporating the trees with crops and also it increases the resilience of the system over time. It enables to:

1. Maximize system productivity on annual basis.
2. Utilize resources with high efficiency through due consideration of various interactions and direct, residual and cumulative effects occurring in soil-plant-atmosphere continuum.
3. Intensify input use vis-à-vis quality of environment.
4. Impart sustainability of farm resources and environment in long-term perspective.

As per weather and harsh climatic situation in arid zone, it has been proved that the single cropping of annual crops under rainfed condition is very risky and non-profitable to the farmers. So that some alternate land use systems which includes perennials like trees and grasses can provide a basis as an insurance against climatic extremes.

The people of western Rajasthan has developed a variety of site-specific agroforestry system since ages. The farmers allowed growing scattered trees and shrubs in the agriculture fields or grazing fields to sustain their life. Such integration of arable crops with trees in the farming systems is a unique, combined, protective and productive system that works on the principles of ecology, economic, productivity and sustainability. They consider these trees in the region a boon particularly in the period of drought when rainfed crops fail. Agroforestry provides 62% fodder, fuelwood, fibre and timber requirement to the rural people. *Prosopis cineraria*-based agroforestry system is most dominant and it covers about 47% total area. About 28% of the total area of western Rajasthan is occupied by *Ziziphus*-based agroforestry system. Other systems such as *Acacia nilotica*, *Tecomella undulata* and *Acacia tortilis* occupied 25% in combine (Tewari et al. 2007).

5.4 Composition of Agroforestry Systems in Arid Regions

The agroforestry systems in arid regions of India are comprised of perennial trees, crops, grasses and livestock. Major perennial components include *Ziziphus mauritiana*, *Prosopis cineraria*, *Emblica officinalis*, *Cordia myxa*, *Punica granatum*, *Capparis decidua*, *Carissa carandas*, *Aegle marmelos*, *Acacia senegal*, *Hardwickia binata*, *Ailanthus excelsa* and *Salvadora oleoides*. These perennial components were traditionally grown in boundaries of farmlands or bunds and the villagers retain the existing trees in their farmland. The major arable crops seen in these tree-based systems are *Pennisetum glaucum*, *Vigna unguiculata, Vigna radiata* and *Zea mays* which are mostly cultivated as rainfed due to the limited quality water availability in the region. Livestock is an integral part of arid village community, which provides a year-round income source to the farming community. Cattle, sheep, goat and camel are the major livestock component seen in western arid Rajasthan. The fodder grass component supports the farmers to meet their livestock feed requirement and they include *Cenchrus setigerus*, *Cenchrus ciliaris* and *Pennisetum purpureum* in the agroforestry system practised in these regions. Some of the important arid agroforestry tree, crop, grass and animal components are given below.

5.4.1 Perennial Components

5.4.1.1 Indian Jujube (*Ziziphus mauritiana*)

The Indian jujube (Ber) of family Rhamnaceae is one of the most ancient cultivated fruit trees in north Indian plains. It grows even on marginal lands or inferior soils where most other fruit trees either fail to grow or give very poor performance. The *Z. mauritiana* is the main species of commercial importance with its several varieties. *Z. nummularia* is prized for leaves (rich in protein) which provide fodder (pala) for livestock. The third one, *Z. rotundifolia*, also bears edible fruits but of smaller size. It is used as rootstock for commercial Indian jujube. The seeds contain saponins, jujubogenin and ebelin lactone. Jujube fruits contain fairly high amount of vitamin C, besides vitamin A, B, protein, calcium and phosphorus (Jawanda and Bal 1978).

5.4.1.2 Indian Mesquite (*Prosopis cineraria*)

Indian mesquite (Khejri) is an important component of farming system and plays a significant role in the economy of Indian desert. It is growing in the arid and semi-arid parts of Rajasthan, Gujarat, Haryana, Punjab, Delhi and some parts of southern India. This tree grows well in all sorts of climatic constraints which is evidenced by the fact that new foliar growth, flowering and fruiting occur during extreme dry months (March–June) when most other trees of the desert remain leafless or dormant. Because of its multiple economic value and suitability in agroforestry systems, it is conserved in arable land where its population is regulated by the farmer. The leaves are used as a fodder to livestock and pods are used as a vegetable. The immature pods are rich in crude protein, carbohydrates and minerals.

5.4.1.3 Indian Gooseberry-Aonla (*Emblica officinalis*)

It is hardy, prolific bearer and highly remunerative even without much care and can be grown in variable agroclimatic and soil conditions. The fruits are recognized for their nutritive, medicinal and therapeutical values and are rich source of vitamin C (4–9 mg g^{-1}), pectin, iron, calcium and phosphorus. The fruit is the main ingredient in chyavanprash and triphala used in Ayurvedic medicine. During the kharif season, moth bean was grown as a common ground storey in rotation with *rabi* crops, i.e. fenugreek, chickpea, mustard and cumin. Higher grain and straw yield were recorded in moth bean-chickpea (497, 1250 kg ha^{-1}) and moth bean-fenugreek (465, 1161 kg ha^{-1}) crop sequence. Among the rabi crops, grain yield of fenugreek, chickpea, mustard and cumin was higher by 28.05, 38.11, 19.96 and 36.05%, respectively, when grown in association with aonla compared to its sole crops. The highest net profit (INR 28260 ha^{-1}) was obtained from moth bean-cumin cropping system, followed by moth bean-chickpea (INR 25024 ha^{-1}) cropping system. Moth bean-chickpea intercropping with aonla supplemented 22.01, 5.00 and 27.90 kg ha^{-1} nitrogen, phosphorus and potassium through crop residues, followed by moth bean-fenugreek crop sequence (Awasthi et al. 2009).

5.4.1.4 Indian Cherry (*Cordia myxa* L.)

Indian cherry which belongs to the family Boraginaceae, locally known as lasoda, is another important fruit plant suitable for arid and semi-arid regions of India. Its fruits and other parts have multiple uses in human health, nutrition and other uses. Green unripe fruits are important as fresh vegetable and pickles during April–May when availability of conventional vegetables is scarce. The species is also important ecologically in providing vegetative cover as tree component of arid farming system, preventing soil erosion and promoting biodiversity. The advantage with this species for agroforestry system is that it offers least competition with rainy season crops since its fruiting season is during summer season when main crops are already harvested. This plant also offers scope in using harvested rainwater for fruit production since it requires irrigation only for 2–3-month period during summer season (April–June) (Table 5.2).

5.4.1.5 Pomegranate (*Punica granatum*)

Pomegranate (anar) of family Lythraceae is an economically important commercial fruit crop of arid and semi-arid regions. Commercial plantations of pomegranate exist in Maharashtra, Gujarat, Rajasthan, Andhra Pradesh and Karnataka owing to its preference for arid climate. Its xerophytic characteristics and hardy nature make it suitable crop for dry, rainfed, pasture and undulating land, where other fruit crops cannot grow successfully.

Table 5.2 *Cordia*-based agroforestry system in arid zone (Awasthi et al. 2007)

Location	Average rainfall (mm)	Crops	
		Rainfed	Irrigated
Jodhpur (Pipad)	290	Pearl millet, cluster bean	Rapeseed, mustard, wheat, green gram
Pali and adjoining areas	490	Vegetables, pearl millet, cluster bean, taramira	Raya, wheat, green gram
Jalore, Sirohi	434–544	Vegetables, cluster bean, pearl millet	Rapeseed, mustard
Bikaner, Barmer	243–350	Pearl millet	Rapeseed, mustard

5.4.1.6 Kair (*Capparis decidua*)

Kair is a multipurpose, perennial, woody shrub or small tree of family Capparaceae which grows widely without much care in the Thar Desert of western Rajasthan. It is highly suitable for stabilizing sand dunes and controlling soil erosion by wind and water. Due to its xerophytic adaptive nature, the plant grows successfully under harsh climatic conditions. Its berry-shaped unripe fruits are rich in carbohydrates, proteins and minerals used as fresh vegetables and in the preparation of pickles. Dehydrated fruits are used in the off season as vegetable either alone or in combination with other dried vegetables. In general, it is highly valued by inhabitants of hot arid areas.

5.4.1.7 *Karonda* (*Carissa carandas*)

Karonda is an evergreen spiny shrub or a small tree up to 3 m height and suitable for arid tropics and subtropics. It grows successfully on marginal and wastelands. The plant is also useful for making attractive thorny dense hedge around any fruit orchard. It yields a heavy crop of attractive berrylike fruits which are edible and rich in vitamin C and minerals especially iron, calcium, magnesium and phosphorus. Mature fruit contains high amount of pectin and, therefore, besides being suitable for making pickle, it can be exploited for making jelly, jam, squash, syrup and chutney, which are of great demand in the international market. Its main flowering season is March–April with fruits maturing during August–September which enables the plants to make best use of monsoon rain. However, some varieties/plant types also flower during October–November.

5.4.1.8 Bengal Quince (*Aegle marmelos*)

Bengal quince (*bael*) of family Rutaceae is an indigenous hardy fruit crop and can be grown successfully in dry areas. It is well known for its nutritional and therapeutic properties. The ripe fruits are laxative and unripe ones are prescribed for diarrhoea and dysentery and are in great demand for native system of medicine such as Ayurvedic.

5.4.1.9 *Kumat* (*Acacia senegal*)

The *A. senegal*-based cropping system produces highly demanded product gum Arabic which possesses the medicinal properties (Shiran et al. 2018). This is an important agroforestry system in arid region which is having high potential of livelihood improvement and it gives high returns to the farmers without much effort in management. The system fulfils both human and animal needs for food by grains and straw from the crops. The additional income is also generated by farmers from gum collecting during the non-cultivating season. Besides that, the tree is fixing nitrogen into the soil and producing prolific fodder through its leaves which can be fed to the farm animals.

5.4.1.10 Anjan (*Hardwickia binata*)

It is commonly known as *Anjan* tree (*Hardwickia binata*) which belongs to Fabaceae family. It is a moderate- to large-sized leguminous tree and is reported to enhance land use efficiency and fulfil multiple demands (timber, fodder and fuel) in arid and semi-arid regions. The leaves are used as a fodder to goats and sole feeding supports the body weight of growing lambs (Patil et al. 2009).

5.4.1.11 *Ardu* (*Ailanthus excelsa*)

Ailanthus excelsa is a lofty deciduous tree and it is widely distributed in semi-arid and arid regions of India. The leaves are rated as highly palatable and protein-rich nutritious fodder for sheep and goats. Therefore, the tree is largely planted on farmlands. The tree has been used successfully in agroforestry for planting around the margins of cultivated fields. An average tree yields about 500–700 kg of green leaves twice a year. Some trees are lopped for green leaves while leaves from others can be lopped, dried and stored for feeding during scarcity period. The leaves are rich in crude protein, ether extract and calcium. Wood of the plant is extensively used for making matchwood boxes and match splints. The species has been extensively used for soil conservation purposes.

5.4.1.12 *Pilu* (*Salvadora oleoides*)

It is found in deserts of Rajasthan and Gujarat. It is an evergreen, small- to medium-sized twisted bushy plant found in mixed xeromorphic woodlands. It makes an excellent fodder for camels. Pilu fruits are edible and seed yields non-edible oil (40–50%) and is used for soap and candle making. The wood is used for making agricultural implements.

5.4.2 Agricultural Crop Components

5.4.2.1 Sorghum (*Sorghum bicolor*)

Sorghum is the most important cereal fodder crop grown in summer/rainy season. Covering the maximum cultivated area among fodder crops, sorghum is grown in all parts of the country except the cool hilly areas. It has high tolerance to drought and excessive rainfall. To avoid prussic acid or cyanide toxicity to livestock, the crop should be harvested at 50% of flowering or after irrigation at the pre-flowering stage.

5.4.2.2 Pearl Millet/Bajra (*Pennisetum glaucum*)

Bajra (*Pennisetum glaucum*) is the most widely grown type of millet. It is well adapted to production systems characterized by drought, low soil fertility and high temperature. It performs well in soils with high salinity or low pH. It is an important forage crop of the arid and semi-arid regions of the country.

5.4.2.3 Maize (*Zea mays*)

Maize (*Zea mays*) is one of the best cereal fodder crops grown during summer, rainy and/or early winter season. It produces rich and nutritious green fodder which is a good source of carbohydrates. It is susceptible to water logging. In early stage up to 35 days after sowing, the crop is drought tolerant.

5.4.2.4 Cow Pea (*Vigna unguiculata*)

Cow pea (*Vigna unguiculata*) legume crop is grown under both irrigated and rainfed conditions. It has a great potential for sustainable agriculture in marginal lands and semi-arid regions of the country. It has great potential as a mixed crop when sown with maize, sorghum and millets to produce an ideal 'legume and cereal' fodder mixture. It is more tolerant to heavy rainfall than any other pulse crop. It suffers from water stagnation and heavy drought. It grows quickly and can yield 25–45 tonnes/ hectare of green fodder. It is also used as green manure crop.

5.4.2.5 Thornless Cactus (*Opuntia ficus-indica*)

It is introduced in Indian arid region for its fodder value as maintenance feed and was observed that if fed along with dry roughages, it reduces the water requirement in goats, sheep and growing cattle. In addition, its high mineral content may reduce the mineral requirement as arid animals often suffer from mineral imbalance (Mathur et al. 2009; Meghwal et al. 2010).

5.4.3 Fodder Grass Components

5.4.3.1 Motha Dhaman/Birdwood Grass (*Cenchrus setigerus*)

It prefers light-textured, sandy soils, adapted to a wider range of soils than is *Cenchrus ciliaris.* It is adapted to arid and semi-arid climates (annual rainfall as low as 200 mm) with a long dry season. Also, it is more drought tolerant than *Cenchrus ciliaris*. It can be cut every 30 days at 10 cm. Once established, it can stand heavy grazing even by sheep. It is moderately palatable and readily accepted by stock.

5.4.3.2 Anjan Ghas/Buffel Grass (*Cenchrus ciliaris*)

Cenchrus ciliaris, commonly known as 'dhaman' in Rajasthan and 'Anjan' in other parts of India, is considered as very drought-resistant species. It is a native of tropical and subtropical Africa, India and Indonesia. It is widely distributed in hotter and drier parts of India and is found in open bush and grassland in its natural habitat. It is widely distributed in the plains of Rajasthan, Gujarat, Punjab and Western UP extending up to foothills of Jammu (an altitude 400 mm). It is polymorphic, perennial and warm season bunch grass with extensive native range in the form of various ecotypes and cytotypes.

5.4.3.3 Napier/Elephant Grass (*Pennisetum purpureum*)

Napier/elephant grass (*Pennisetum purpureum*) is supposed to be native of tropical Africa. It is most susceptible to frost. The crop becomes ready for first cutting about 3 months after its planting and thereafter each subsequent cutting may be taken at about 2 months interval. However, it depends upon the vegetative growth of the crop. On an average 6–8 cuttings can be taken which gives about 40–60 tonnes of green fodder per hectare.

5.4.4 Livestock Components

Crop-livestock production has served as the sustainable livelihood resource option for people living in the arid and semi-arid regions. Goat and sheep with its multifacet utility for wool, meat, milk, skins and manure form an important component of rural economy particularly in the arid, semi-arid and mountainous areas of the country. Milk is not a major part of their diet in arid and semi-arid region and the main objective of keeping cattle was for draught purposes and as source of fuel and manure.

Major livestock breeds in arid region of Rajasthan are as follows (Mathur 2018):

Cattle: Tharparkar, Rathi, Nagori and Kankrej.
Sheep: Marwari, Jaisalmeri, Chokla, Nali, Magra, Pugal and Sonadi.
Goat: Marwari, Kutchi and Parbatsari.
Camel: Bikaneri and Jaisalmeri.

5.5 Traditional Agroforestry Systems

Traditional agroforestry systems may be described as a set of age-old agroforestry systems which are generally devoid of intentional intensified cultivation of agricultural or forage crops and which have been practised across the world with varying structure, function, socioeconomic attributes and ecological services (Viswanath et al. 2018). Agroforestry of arid region is connected with people traditionally, as it provides all sort of ecosystem services, viz. food, fruit, fodder, shelter and shade, and also improves soil fertility in the long term. In arid regions, people do not plant trees in their farmlands; rather they protect and take care of trees randomly growing plants regenerated in their farmlands (Fig. 5.1). This traditional system has evolved

Fig. 5.1 Traditional agroforestry practice in arid parts of Rajasthan (Karnu, Nagaur District, Rajasthan) (Photo by Kamlesh Pareek)

much before the presently practised fossil fuel-based agricultural system came into existence.

Considering the climatic and edaphic features of the region, local people preferred various drought hardy and multipurpose/multiuse tree and shrub species for survival in harsh climatic conditions. During normal rainfall years, this system provides sustainable food, fodder and fruit production. *Prosopis cineraria*, *Tecomella undulata* and *Ziziphus nummularia* are major vital tree species of the traditional agroforestry system, which serve as lifeline of arid people of Rajasthan. The desert top feeds like Khejri leaves (loong) and Bordi leaves (pala) provide sustenance when the ground cover is depleted. It is for this reason that palatable and nutritious top feed species have such importance in the desert ecosystem. Moreover, they sustain livelihood during the crop failure by producing food, fodder and timber (Malhotra 1984; Arya et al. 1992).

The area covered by *P. cineraria* is 46.3% distributed in Barmer, Bikaner, Churu, Ganganagar, Jalore, Jodhpur, Jhunjhunu, Nagaur and Sikar followed by *Ziziphus nummularia* covering 27% of Barmer, Bikaner, Jaisalmer and Jodhpur districts. Among major traditional systems, least percentage was covered by *Tecomella undulata* covering 6.7%, distributed mostly in Barmer district (Tewari and Singh 2006). The traditional agroforestry systems and its intercropping components prevailing in different districts of arid regions are presented in Table 5.3.

5.6 Improved Agroforestry Systems in Arid Region

Tree-based land used systems is the mainstay of arid regions because of harsh and inconsistent climate conditions. In the severe drought conditions when crop fails the trees act as source of survival for man as well as livestock. The most common systems seen and studied in these regions include:

Table 5.3 Major components of traditional agroforestry models in arid Rajasthan (Source: Tewari and Singh 2006)

S. No	District	Main tree/shrub species	Rainfall (mm)	Intercrops	Prominent grass species	Major soil
1.	Jaisalmer	*Calligonum polygonoides*, *Ziziphus nummularia*, *Prosopis cineraria*, *Capparis decidua*	100–200	Mung bean, pearl millet and cluster bean	*Lasiurus indicus*	Sandy plain dune
2.	Sri Ganganagar	*Prosopis cineraria*, *Acacia nilotica* subsp. *indica*, *Acacia tortilis*	200–300	Rainfed—Pearl millet, mung bean, cluster bean. Irrigated—Wheat, cotton, rice and mung bean	*Lasiurus indicus*	Indus alluvial
3.	Bikaner	*Ziziphus nummularia*, *Prosopis cineraria*, *Calligonum polygonoides*, *Acacia jacquemontii*	100–400	Mung bean, moth bean, cluster bean and pearl millet	*Lasiurus indicus*	Sandy plain
4.	Barmer	*Prosopis cineraria*, *Ziziphus nummularia*, *Tecomella undulata*, *Capparis decidua*	200–400	Rainfed—Pearl millet, mung bean and cluster bean	*Lasiurus indicus*, *Cenchrus ciliaris*	Sandy plain dune
5.	Jodhpur	*Prosopis cineraria*, *Ziziphus nummularia*, *Capparis decidua*, *Acacia Senegal*	200–400	Pearl millet, mung bean and cluster bean	*Cenchrus ciliaris*	Sandy plain, brown light loam and grey brown loam
6.	Churu, Jhunjhunu and Sikar	*Prosopis cineraria*, *Gymnosporia montana*, *Ziziphus nummularia*	300–600	Rainfed—Pearl millet, mung bean. Irrigated—Wheat, mung bean and mustard	*Lasiurus indicus*, *Cenchrus ciliaris*	Sandy plain and dune

(continued)

Table 5.3 (continued)

S. No	District	Main tree/shrub species	Rainfall (mm)	Intercrops	Prominent grass species	Major soil
7.	Nagaur	*Prosopis cineraria*, *Acacia nilotica*	300–500		*Cenchrus ciliaris*	Grey brown loam and sandy plain
8.	Jalore	*Prosopis cineraria*, *Salvadora oleoides*, *Acacia nilotica* and *Punica granatum*	400–500	Pearl millet, mung bean, isabgol, sorghum and cumin	*Cenchrus ciliaris*	Grey brown loam and sandy plain
9.	Pali	*Acacia nilotica* subsp. *indica*, *Acacia nilotica* var. *cupressiformis*, *Acacia leucophloea*, *Acacia catechu*, *Salvadora oleoides*	400–600	Sorghum, pearl millet, mung bean and cluster bean	*Cenchrus ciliaris* and *Cenchrus setigerus*	Sandy plain, brown light loam and grey brown loam

1. Agri-silviculture.
2. Silvo-pastoral.
3. Agri-horticulture.
4. Horti-pasture.

Agri-silviculture systems are those in which both crops and trees/shrubs are grown on same unit of land and products are obtained from both components. Livestock rearing is the next important occupation of the people of arid areas after agriculture. Silvo-pasture in common is the practice of raising grasses along with fodder trees; but in arid regions these systems are developed traditionally by people. In light of increasing pressure on land resources, Central Arid Zone Research Institute (CAZRI), Jodhpur, initiated systematic studies on agroforestry systems in the early 1970s. Since then a number of agroforestry practices were studied and modified in order to enhance overall productivity and economic returns from the system in the arid region.

5.6.1 Agri-Silviculture System

In arid regions, farmers raise the trees like *Prosopis cineraria*, *Ziziphus nummularia*, *Tecomella undulata*, *Salvadora oleoides*, etc., in the crop fields as well as bunds along with crops like pearl millet, moth bean, mung bean, cluster bean, etc., along with these tree species. This is the most popular system in the areas receiving rainfall between 200 and 400 mm yr^{-1}. Many researchers have reported Khejri (*Prosopis cineraria*) as one of the suitable agroforestry trees for the region. Studies on various intercroppings with *Prosopis cineraria* had no adverse effect on both crop and tree although in some cases the yield has increased in cropping along with trees (Bishnoi and Singh 2009; Roy et al. 2011) (Fig. 5.2). It was found that when crops are raised with trees the total productivity per unit land as well as the biological activities raises when compared to sole arable farming (Tanwar et al. 2014). The research on tree density extensively carried out in this region showed 833 stems per ha did not adversely affect the yields of intercrops during the first 2 years of tree growth (Gupta et al. 1998). Slightly higher values of net returns (INR 8450 and INR 14949 and B/C ratio 1.56 and 2.08) were observed with Khejri plantation in 2 years as compared to other tree species (Sharma 2015). *Prosopis cineraria*-based agroforestry system with crops like pearl millet, *Brassica* spp., have been reported substantially increased crop yield compared to sole crop (Roy et al. 2011). The grain yield of pearl millet, green gram and cluster bean was higher in association with *Prosopis cineraria* as compared to arable farming (CAZRI 2015). Also the wider spacing (10 m × 10 m) of *Ailanthus excelsa* trees was not only favourable for the growth of associated crops like moth bean and pearl millet but the overall growth of trees was also enhanced. Studies with crops like cluster bean and moth bean were cultivated with *P. cineraria*, *Ailanthus excelsa* and *Tecomella undulata* had improved the soil fertlity status and tree species had no adverse effect on growth and grain yields of crops and vice versa.

Fig. 5.2 *Prosopis cineraria*—pearl millet-based agri-silviculture system in Nagaur district of Rajasthan (Photo by Kamlesh Pareek)

5.6.2 Silvo-Pastoral System

Silvo-pasture system is an ideal system for arid and semi-arid regions of India as it assures the availability of fodder for areas with big population of livestock. The livelihood of arid region in India is largely dependent on livestock; in very low rainfall areas growing crops is not feasible so people raise livestock to earn their livelihood; therefore silvo-pastoral systems are the inherent part of land use systems in these regions. Also traditionally village people are protecting the piece of land as orans or gochar in which no tree cutting is allowed and only animals are allowed to graze the grasses and browse the leaves of trees. Farmers in these areas encourage growing *Prosopis cineraria* (Khejri), ber (*Ziziphus*) and babool (acacia) trees in the crop fields (Patil and Pathak 2013) (Fig. 5.3). There is a common belief that crop productivity increases in association with Khejri trees and in addition it provides a good feed for small and large animal production system. Studies carried out in arid region of Gujarat on grasses showed, under silvi-pastoral systems, the soil organic carbon under grasses improved from 0.47 to 0.58% (Shamsudheen et al. 2009) and *Cenchrus ciliaris* grass was more productive in fodder yield when compared with *C. setigerus* and grass yield as well as tree growth was found to be superior when grasses were grown with neem tree (Dayal et al. 2008). The fodder yield of grasses did not differ significantly due to association of trees with grasses in a silvo-pasture system with 20 years of cultivation. In a study carried out in arid Rajasthan on the highest dry matter yield was recorded in silvo-pasture system than sole pasture crop. Dry matter yield in different silvo-pastoral systems was varied from 27.00 Mg ha^{-1} to 26.39 Mg ha^{-1} compared to sole crop (22.59 Mg ha^{-1}). Intercropping of grasses with legumes in association with *H. binata* appears to be highly suitable for obtaining higher productivity of quality fodder in a silvo-pastoral system for an arid environment (Patidar and Mathur 2017) (Fig. 5.4).

5.6.3 Agri-Horticulture and Horti-Pasture

Present day, the farmers of arid regions are moving towards more economic crop. So they are adding horticultural components in their existing system. Traditionally farmers raise crops like pearl millet, moth bean, mung bean and cluster bean along with *Ziziphus* spp., *Cordia myxa* (*gonda*) and *Capparis decidua* (*kair*) trees. A sustainable model for nutritional and income security for the arid regions is found to be goose berry-based cropping system which consists of goose berry + ber along with moth bean or fenugreek (Awasthi et al. 2007). The yield of *Ziziphus*-based cropping system has been reported higher than the monoculture of either trees or crops by many workers. The B/C ratio of ber + mung was 2.02 and ber + cluster bean was 2.15 which was comparatively higher than the sole ber (2.1), sole green gram (1.42) and sole cluster bean (1.93) (Meghwal and Henry 2006). Intercropping in ber orchard produced higher grain yield of intercrops by 5–20% over their sole cropping and intercropping is promising particularly during juvenile period of fruit plantation (Bhandari et al. 2014). In addition to the traditional fruit trees, guava, karonda and

Fig. 5.3 *Prosopis cineraria* (Khejri) and *Pennisetum purpureum* (Napier)-based silvo-pastoral system in Pali District of Rajasthan (Photo by Noor Mohamed MB)

Fig. 5.4 *Cenchrus setigerus* (Daman) with *Hardwickia binata (*Anjan*)*-based silvo-pastoral system in Pali District of Rajasthan (Photo by Noor Mohamed MB)

pomegranate are emerging as promising components of agri-horticulture system for enhancing the productivity of arid lands. Intercropping of fodder grasses along with horticulture trees intensifies the productiveness of the particular system. Recommended agri-horti crop components for rainfed and irrigated conditions of Indian arid regions were optimized for sustainable site resource utilization (Table 5.4) by the researchers. *Cenchrus ciliaris* with ber (6 m × 6 m) was very

Table 5.4 Composition of agri-horticultural systems for Indian arid regions (Bhandari et al. 2014)

Growing conditions	Tree component			Crops
	High storey	Medium storey	Ground storey	
Rainfed (150–300 mm)	Bordi and Indian mesquite	Jhar ber	Cucurbits and guar	Guar, moth bean, pearl millet and sesame
Rainfed (300–500 mm)	Indian cherry, Indian jujube and Indian mesquite	Jhar ber	Cowpea, cucurbits, guar and Indian bean	Cowpea, guar, green gram, moth bean, pearl millet and sesame
Irrigated	Bengal quince, Indian gooseberry Indian jujube and Indian mesquite	Guava, kinnow, karonda, lime, pomegranate and sweet orange	Brinjal, chilli, cole crops, cucurbits, garlic, okra, onion, peas, root/leafy vegetables and tomato	Chickpea, green gram, groundnut mustard and seed spices

Fig. 5.5 *Ziziphus mauritiana* and *Cenchrus ciliaris*-based horti-pastoral system in Didwana in Nagaur District of Rajasthan (Photo Kamlesh Pareek)

profitable where the dry grass production was 1.55 Mg ha^{-1} year^{-1} and the fruit, leaf fodder and fuelwood production from ber was 2.77, 1.87 and 2.64 Mg ha^{-1} year^{-1}, respectively (Tewari et al. 1999) and it could sustain 554 Tharparkar cattle days/ha with 60% pasture utilization (Tanwar et al. 2014). The yield of leaf fodder (3.93 kg plant^{-1}), fruit (36.84 kg plant^{-1}) and fuelwood (23.31 kg plant^{-1}) in ber (*Ziziphus mauritiana*) was higher in association of *Cenchrus setigerus* than *Cenchrus ciliaris* (Fig. 5.5).

5.7 Conclusion

Agricultural development in the hot arid region is really a challenging task due to the hostile climate, erratic rainfall, infertile and unproductive soils and intense biotic pressure from grazing animals. And about 95% area of the arid western Rajasthan depends upon monsoon rains for crop production. In such condition agriculture alone cannot be a dependable enterprise and it is uncertain. The arid region has widely scattered trees/shrubs of various species along with the crops of food grain and fodder grasses. Hence the desert dwellers with their traditional wisdom are integrating forestry into farming since ages as an example of traditional agroforestry in order to provide stability and generate assured income. Agroforestry is the way to life in arid western Rajasthan and this approach has been widely advocated as a means to harmonize use of scarce inputs so as to make production system sustainable and climate smart. And also, it will lead to meet the need of arid zone people in terms of balanced diet, fuelwood, fodder and other useful products.

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6 Land Use Management by Smallholders' Households as a Promising Way for Synergies Between the Rio Conventions: Case Study in Semi-Arid Areas of Cameroon

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Abstract

Land use management by smallholders' households in dry landscapes can be an important entry point for contending desertification, climate change mitigation and biodiversity conservation. Strategies employed by these households to address land use problems can bring together efforts of the three Rio conventions. Identifying the typology of the current land use can lead to understand how biomass can be managed toward climate change mitigation efforts such as Clean Development Mechanism and Reduce Emissions from Deforestation and Forest Degradation including conservation, sustainable management of forests and enhancement of forest carbon stocks. From this perspective, a survey of 598 households in six divisions in the Far North Cameroon was conducted using a semi-structured questionnaire.

This study reveals six main land uses, some of which overlap: cropped field (managed by 95% of local households), grassland (34%), settlements (28%) and forest lands (76%) that significantly contribute to local livelihoods. Non-timber forest products, fuelwoods, timbers and fodders are the main products provided by these land uses. Besides the products, some management practices including agroforestry, urban and peri-urban forestry and forest plantation have been

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identified to contribute to combat desertification and conserve biodiversity and climate change mitigation and adaptation in this semi-arid area of Cameroon.

Keywords

Land use change · Household characterization · Biodiversity conservation · Climate change · Rio Convention

6.1 Introduction

Human activities in the land use, land use change and forestry (LULUCF) sectors are recognized among the main causes of land degradation, biodiversity loss and climate change. Land use refers to the total of human's activities and inputs undertaken in a certain land cover type, while land use change refers to a transformation in terms of use or management of land by humans, which is accompanied by a change in land cover (IPCC 2000). Several studies have showed the links between land use change, biodiversity loss, climate change and desertification (Pando-Moreno et al. 2004; de Chazal and Rounsevell 2009; Oliver and Morecroft 2014; Foley et al. 2005).

The LULUCF sector has an important place in the Convention on Biological Diversity. Decisions adopted by the conference of the parties to the convention on biological diversity at its fifth meeting, held in Nairobi, considered land use change as a proximate cause of biodiversity loss (CBD 2000). Gonzalez et al. (2012) detected significant 1960–2000 species richness decline of 21% across the Sahel in which northern Cameroon is a part. This issue has also been identified by the Cameroon National Biodiversity Strategies and Action Plan (NBSAP) which attributed biodiversity loss to forest and savanna conversion to industrial farming systems and urban development (Republic of Cameroon 2012).

Land use change and climate change are interlinked (Teixeira et al. 2006; IPCC 2013). The first national inventory of greenhouse gas (GHG) emission published in Cameroon's "Initial National Communication" to the United Nations Framework Convention on Climate Change (UNFCCC) (MINEP 2006), by the Environment and Forest Minister, highlights the key role of LULUCF activities in climate change. This inventory clearly established that the highest levels of GHG emissions are associated with the agriculture and land use change. Agriculture and land use change are responsible respectively of 38% (16,435 $GgECO_2$) and 50% (22,186 $GgECO_2$) of total GHG emission in the country (MINEP 2006).

The Secretariat of the United Nations Convention to Combat Desertification (UNCCD) (1994) recognized land use as the direct factor of land degradation in Africa and worldwide. The article 9 of the UNCCD recommends to each affected African country party to "identify and analyze the constraints, needs and gaps affecting development and sustainable land use and recommend practical measures to avoid duplication by making full use of relevant ongoing efforts and promote implementation of results".

Compared to the humid area of the country belonging to the Congo Basin, the implementation of national environmental policies and programmes developed to address such problems until now have been happening in the context of limited information in land use management. Cameroon like other countries of Central Africa is covered by humid and dry landscapes. Unfortunately, because of the high interest in preserving the Congo Basin forests, much of the research and conservation activities have so far been focused in the southern part of the country and very little information exists in the northern dry landscape. It remained somewhat poorly understood the links between human activities and environmental dynamics in semi-arid areas of Cameroon.

Land use management by smallholders' households can be an important entry point to reduce desertification, mitigate climate change and conserve biodiversity. According to the Secretariat of the United Nations Convention to Combat Desertification (UNCCD) (1994), LULUCF activities can play an important role in reducing net GHG emissions to the atmosphere through conservation of existing carbon pools, sequestration by increasing the size of carbon pools and substitution of fossil fuel energy by use of modern biomass. Sustainable land use can also address human activities such as overexploitation of plants and trampling of soils that exacerbates dryland vulnerability (Millennium Ecosystem Assessment 2005). Thus, the implementation of land use, land use change and forestry activities can be potential synergies between existing multilateral environmental agreements.

Recent research studies highlighted some indigenous strategies that have been practised in the Sahel and elsewhere in Africa. Some of them describe mitigation and adaptation strategies that have enabled local population to reduce their vulnerability to climate variability and change (Nyong et al. 2007; Egeru 2012; Kpadonou et al. 2012), while others underlined traditional practices in biodiversity conservation and measures to combat desertification (Oke and Jamala 2013; Fraser et al. 2006; Hens 2006; McNeely and Scroth 2006). The present study will (i) identify and characterize the main land use in the semi-arid area of Cameroon and (ii) analyse the management of plant resource in those land use (ii) and their role in biodiversity conservation, mitigating climate change and desertification.

6.2 Study Area, Data Collection, and Data Analysis

6.2.1 Study Area

The Far North Region of Cameroon lies between 9°40′ and 13°05′ north and 12°15′ and 16°45′ east. It covers 34,263 square kilometre (Tabopda Wafo 2008) and represents 7.21% of the total country land area. This region is bordered to the north and the east by the Republic of Chad, to the west by the Federal Republic of Nigeria and to the south by the North Region of Cameroon (Fig. 6.1). The Far North Region is one of the most populated regions of the country with 3.709691 million, which represents 17.4% of Cameroon's overall population and a density of 90.8 inhabitants per square kilometre (Mbarga 2010).

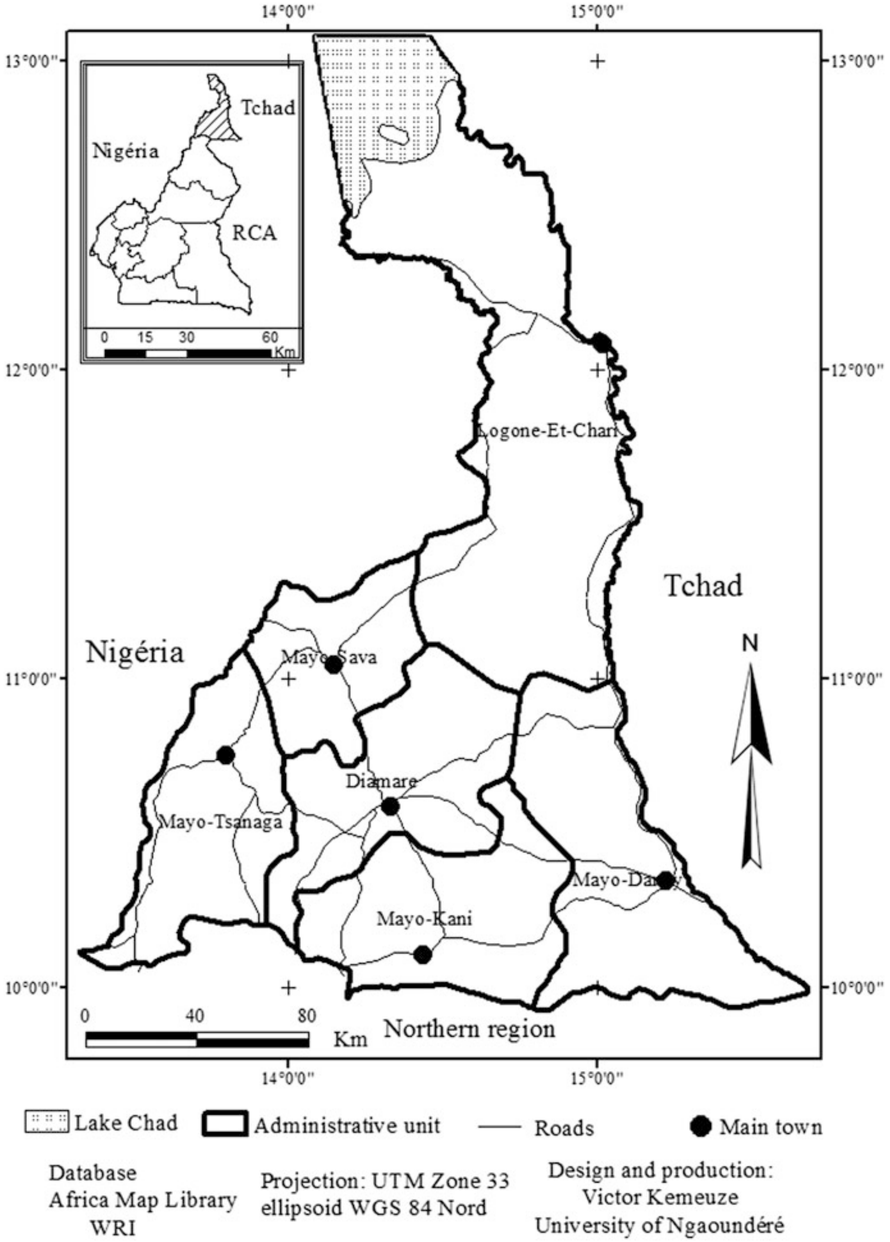

Fig. 6.1 Location of the study area

The semi-arid zone of Cameroon is the hottest and driest part of the country. The climate of the region is characterized by the dry and wet seasons. Annual total precipitation is between 400 and 1000 mm and depends on the landscape shape. Annual average mean temperature is between 25 °C and 27 °C in the cooler seasons

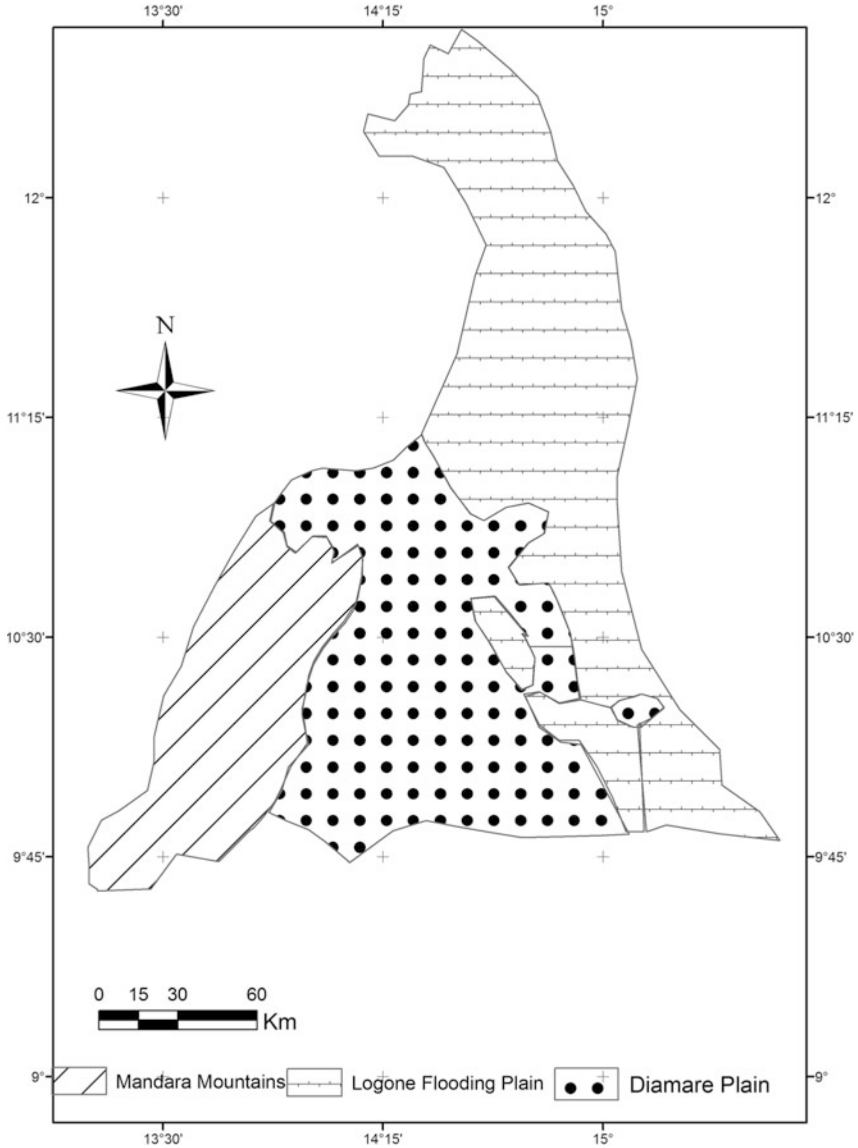

Fig. 6.2 Ecological zones of Far North Region

(September–February) and 27 °C and 30 °C in the warmer seasons (March–August) (McSweeney et al. 2012).

The Far North Region contains six divisions which include Diamare, Logone and Chari, Mayo Danay, Mayo Kani, Mayo Sava and Mayo Tsanaga. These divisions were grouped into three main ecological zones (Fig. 6.2) according to their climatic, floristic and topographic affinities and socio-economy characteristic: (a) regularly flooded Logone plain with low population density with shrub steppe and flooded grassland, (b) the Mandara Mountain zone with woody savanna and (c) the plain of Diamare with high population density (Tabopda Wafo 2008) and woody steppe and shrub savanna (Konga Mopoum 2013). We assume that management practices of land and floristic composition should be different according to the main above zones.

6.2.2 Data Collection

Data were collected in two main steps.

Step 1: Identification and Characterization of the Main Land Use
Semi-structured interviews and focus group discussions were used to identify the main land use of the study area. A total of ten focus group discussion was conducted with questionnaire in several king palaces including Lara, Kaele, Pette and Yagoua in Diamare plain; Goulfey, Guirvidig, Waza and Maga in Logone plain; and Mogode and Rhumsiki in Mandara Mountains. In each village at least six notables participated in group. The discussion was focused on land use description and management practices. Semi-structured interviews were conducted with four local administrative in each division. The data collected were completed by field observations.

Step 2: Land Use Management Assessment
Household semi-structured interviews were conducted using questionnaire in the three main ecological zones. The questionnaire was only based on the use and management of plant resources in the main land use types. The management criteria used were as follows: nature of plant species (natural or planted) in the land use, harvesting technics and availability of exploited resources. At the end of this step, a total of 598 households have participated to our interview with 150 in Logone plain (25% of households), 199 in Mandara Mountains (33%) and 249 in Diamare plain (42%). This activity has been carried out in Lara, Kaele, Guidiguis, Pette and Yagoua in Diamare plain; Goulfey, Guirvidig, Waza and Maga in Logone plain; and Gouria, Mokolo, Mogode and Rhumsiki in Mandara Mountains.

6.2.3 Data Analysis

The classification and characterization of land use was done using Intergovernmental Panel on Climate Change (IPCC) good practice guidance (GPG) for land use, land use change and forestry (LULUCF) (IPCC 2003) and FAO land cover classification system (Di Gregorio and Jansen 2000). The GPG for LULUCF describes six land-based structures for reporting emissions and removals of greenhouse gases. These land-based structures include forest land, cropland, grassland, wetlands, settlements and other lands (lands that do not fall within any of the other categories). The data collected were computed using XLSTAT-Pro 7.5 for statistical analysis. These data

Table 6.1 Distribution of land use into ecological zone (+ = present; − = absent)

Land use	Mandara Mountains	Diamare plain	Logone plain
Cropland	+	+	+
Grassland	−	−	+
Settlements	+	+	+
Wetlands	+	+	+
Forest land	+	+	+
Other lands	+	+	+

were presented per ecological zone. Significant different means were separated using one-way analysis of variance (ANOVA) with Student-Newman-Keuls (SNK) test at confidence interval of 95% (Golding et al. 2000).

6.3 Main Land Use of the Far North Region of Cameroon

A total of six main land uses was identified in the Far North Region of Cameroon according to the IPCC good practice guidance for land use, land use change and forestry. These include cropland, forest land, grassland, wetlands, settlements and other lands (rock, sandy area) (Table 6.1).

The croplands include farming systems (treeless farms and agrosystem parkland), fallow, orchards and gum arabic's plantation. The forest lands include forest plantation, steppe, shrub savanna and tree savanna. Grassland only included periodically flooded grassland, while the settlement comprises urban forest.

According to land cover classification system based on dominant life form and density of woody plants, Table 6.2 presents the characterization of the main land use and the main uses of these zones based on field observations. It was found that many of these land uses are areas of perennial and seasonal grazing, non-timber forest product (NTFP) and fuelwood collection, straw collection for house and fence building, recreation and windbreak.

6.4 Household Characterization

Table 6.3 presents the main characteristics of the households in each ecological zone. The average size of household is eight persons in the whole study area. At least 72% and 60% of head of household is unschooled respectively in Mandara Mountains and Logone plain. The sample population in the study area is mainly farmers and breeder.

Agriculture is the main source of household's income in the Diamare plains and Mandara Mountains. This activity is followed in those ecological zones by breeding, fuelwood and NTFP exploitation (Table 6.4).

Table 6.2 Characteristics of the main land uses of the semi-arid area of Cameroon

Land use	Dominant life form	Relative density of woody plants (%)	Mains uses
Forest land	Shrubs	≤40%	– Perennial grazing – NTFP collection – Fuelwood collection – Timber collection – Straw collection for house and fence building
	Trees	>40	– Seasonal grazing – NTFP collection – Fuelwood collection – Timber collection – Straw collection for house and fence building
Grassland	Grass	≤1%	– Seasonal grazing – NTFP collection – Straw collection for house and fence building
Wetlands	–	0%	– Livestock's watering – Other uses
Settlements	Trees	Between 10% and 20%	– Windbreak – Soil erosion protection – NTFPs collection – Fuelwood collection – Timber collection – Recreational area
Croplands	Treeless	0%	– Market garden – Cotton production – Subsistence crops – Paddy field
	Shrubs	≤1%	– Market garden – Cotton production – Subsistence crops – Seasonal grazing – NTFP collection – Fuelwood collection – Straw collection for house and fence building
		≥60%	– Orchards – Gum arabic plantations
	Trees	≤10%	– Market garden – Cotton production – Subsistence crops – Seasonal grazing – NTFP collection – Fuelwood collection
		≥60%	– Orchards

(continued)

Table 6.2 (continued)

Land use	Dominant life form	Relative density of woody plants (%)	Mains uses
Other lands	Bare laterite soil	0	–
	Bare sandy soil		–
	Rock	0	–
	House	0	–
	Burning area	0	–

Table 6.3 Household characterization in the main ecological zones of the semi-arid area of Cameroon

Variables	Mandara mountains	Diamare plain	Logone plain	Average	*p*-value
Sex (%)					
Female	6.2^{b}	8.3^{b}	22.7^{a}	10.9	0.02
Male	93.8^{a}	91.7^{a}	77.3^{b}	89.1	0.02
Age (year)	46.2^{a}	39.3^{b}	44.4^{a}	42.3	0.00
Marital status (%)					
Single	0.9^{b}	9.2^{a}	7.7^{a}	6.5	0.06
Married	98.1^{a}	88.6^{b}	81.9^{b}	89.8	0.01
Widower	1.0	2.2	10.4	3.7	0.01
Number of person/household					
Number of people	9^{a}	7^{b}	8^{ab}	8	0.03
Education (%)					
Not schooling	72.2^{a}	25.9^{b}	60.5^{a}	46.5	0.00
Primary school	21.3	26.1	18.6	23.1	0.6
Secondary	6.5^{b}	46.1^{a}	20.9^{a}	29.4	0.00
University	–	1.9	–	0.9	–
Principal occupations (%)					
Farmer	92.5	92.4	61.3	82.1	0.11
Craftsman	2.0	2.4	0.7	1.7	0.4
Trader	1.0^{a}	0.4^{a}	8^{b}	3.1	0.00
Breeder	43.2	77.5	44.0	54.9	0.09
NTFP operator	20.6	17.3	20.7	19.5	0.7
Fisher	–	–	2.0	0.7	–
Others	3.0^{b}	2.4^{b}	9.3^{a}	4.9	0.01

Means not sharing the common letter in a column are significantly different at $p = 0.05$ probability

Table 6.4 Main household source of income in the semi-arid area of Cameroon

	Diamare plain $N = 249$	Logone plain $N = 150$	Mandara Mountain $N = 199$	Average	p
Agriculture	58.5^{a}	17.2^{b}	57.0^{a}	49.1	<0.0001
Orchards	3.9^{a}	0.5^{b}	1.5^{ab}	2.5	0.06
NTFPs	5.4^{a}	0.8^{b}	2.1^{a}	3.4	0.09
Fuelwood	3.8^{b}	12.1^{a}	1.81^{b}	4.9	0.04
Breeding	28.4^{a}	28.3^{a}	12.5^{b}	23.9	0.01
Other	0.9^{b}	41.2^{a}	25.1^{a}	16.6	<0.0001

Means not sharing the common letter in a column are significantly different at $p = 0.05$ probability

Table 6.5 Main products exploited by farmers (% of household managing the land use) of the semi-arid area of Cameroon

Land use types	Product	Diamare plain $N = 249$	Logone plain $N = 150$	Mandara Mountain $N = 199$	Average	p	F
Croplands	NTFPs	67.3^{a}	72.0^{a}	80.2^{a}	72.0	0.59	0.5
	Fuelwoods	69.8^{a}	15.3^{b}	76.9^{a}	61.3	0.00	8.9
	Timber	6.6^{a}	0.3^{a}	2.7^{a}	4.3	0.12	2.3
	Fodders	81.4^{a}	37.9^{b}	52.4^{a}	64.6	0.00	10.9
Settlements	NTFPs	17.7^{b}	60.2^{a}	2.2^{b}	21.4	<0.00	14.6
	Fuelwoods	18.5^{a}	0.8^{b}	2.8^{b}	10.5	0.01	5.6
	Timber	3.7^{a}	7.9^{a}	0.8^{a}	3.7	0.19	1.8
	Fodders	3.3	–	0.4	1.8	0.39	1.0
Grasslands	NTFPs	27.9^{b}	54.0^{a}	–	24.9	0.00	7.7
	Fuelwoods	1.7^{b}	55.1^{a}	–	11.6	0.00	41.9
	Timber	33.4^{a}	4.1^{b}	–	18.0	0.01	5.9
	Fodders	34.0^{a}	1.6^{b}	0.2^{b}	17.9	0.00	7.3
Forest lands	NTFPs	70.8^{a}	65.4^{a}	54.4^{a}	65.0	0.32	1.2
	Fuelwoods	69.1^{a}	9.8^{b}	27.1^{b}	45.4	0.00	17.2
	Timber	43.2^{a}	16.0^{b}	41.2^{ab}	37.4	0.12	2.3
	Fodders	37.7^{a}	8.7^{b}	9.7^{b}	24.5	0.02	4.3

Means not sharing the common letter in a column are significantly different at $p = 0.05$ probability

6.5 Key Products and Services of Land Uses

The main services provided by these land uses include provisioning, supporting, regulating and cultural services. The key provisioning services are NTFPs, fuelwood, timber and fodders (Table 6.5).

Croplands and forest lands are the major land uses which provide most of the NTFPs and fuelwoods. A total of 75 citations of local names of plant species have been recorded as NTFPs exploited in cropping systems. Only 53 of them have been identified. Of these identified plants species, 43 are natives while ten are exotics. The top ten most cited NTFPs of cropland are *Adansonia digitata*, *Ziziphus mauritiana*, *Mangifera indica*, *Faidherbia albida*, *Psidium guajava*, *Citrus aurantifolia*, *Ximenia americana*, *Azadirachta indica*, *Acacia nilotica* and *Ziziphus spina-christi.* A total of 48 plant species have been cited as exploited as fuelwoods in cropping systems with six exotic species. The top ten species include *Faidherbia albida*, *Balanites aegyptiaca*, *Ziziphus mauritiana*, *Acacia* sp., *Azadirachta indica*, *Anogeissus leiocarpa*, *Tamarindus indica*, *Terminalia macroptera*, *Senna siamea* and *Mangifera indica* (Appendix).

The leafy stems of cereals, oilseed cakes, cottonseeds, straw and hay are the main products used as fodder by farmers in cropland followed by *Hyphaene thebaica* and *Borassus aethiopum*. Woody species include *Faidherbia albida*, *Anogeissus leiocarpa*, *Ziziphus* spp., *Balanites aegyptiaca* and *Tamarindus indica* (Appendix).

As for the other services, many plant species cited in cropping systems contribute to soil fertilization. These species include *Acacia* spp. (*Acacia hockii*, *A. gerrardii*, *A. nilotica*, *A. senegal*, *A. seyal*), *Faidherbia albida*, *Leucaena* sp., *Piliostigma reticulatum*, *P. thonningii*, *Prosopis africana*, *Sesbania sesban* and *Tamarindus indica* (Appendix). Among the forest lands, some sacred grooves have been recorded in the Diamare plain and Mandara Mountains. These areas are mostly used for cultural purposes by communities of these zones.

6.6 Management of Natural Resources in Land Uses

Only 5% of households in Mandara Mountain are treeless farm owners followed by 20% in Diamare plain and 70% in Logone plain (Fig. 6.3).

Of the total plants cited in the croplands, most of them have been preserved by local farmers (74%) during establishment of the farm. Systematic cutting is the main

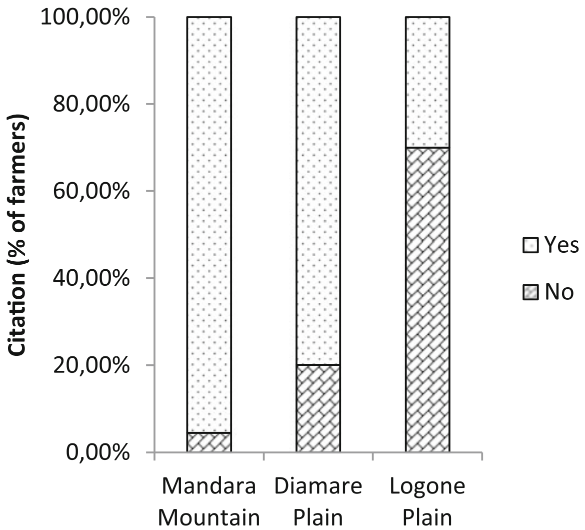

Fig. 6.3 Percentage of households with treeless farms

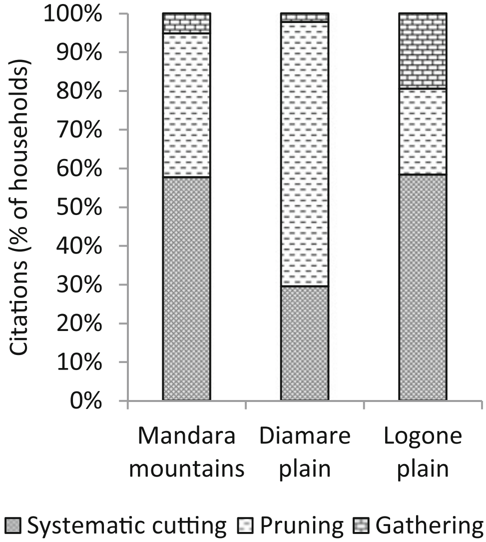

Fig. 6.4 Harvesting methods of plant resources

harvesting method in Mandara Mountains and Logone plain (done by 58% of households). In the Diamare plain, pruning is the most frequent harvesting technic followed by systematic cutting and gathering (Fig. 6.4). According to the smallholder's farmers these different techniques are necessary to maintain the quantity of trees in the farming systems.

In the whole Far North Region, a total of 12% of farmers argue that the quantity of trees in their farms is constant since their creation while 42% and 42% argue for the increasing and decreasing tree quantities, respectively, and then 4% no idea.

As far as the prospects to increase the number of trees in farming systems are concern, 40% of farmers in the Logone plain disagreed while only 7% agreed and 52% had no opinion (Fig. 6.5).

6.7 Land Use and Biodiversity Conservation

Land use in semi-arid areas of Cameroon has good implications for plant species conservation according to the assertion of local famers. A total of 141 citations of local plant names have been recorded during interviews. These include 93 different citations in croplands, 83 in forest lands, 47 in settlements and 38 in grasslands. Only 97 plant species including 69 in croplands (agroforests, orchards, fallows and gum arabic's plantation), 59 in forest lands, 37 in settlements and 32 in grasslands (Fig. 6.6) were identified during field survey in the whole study area. If these citations are confirmed by field assessment, land use types of semi-arid areas of Cameroon will be considered among the richest habitat for plants in the Sahel.

Agroforestry parkland is recognized as a good way to conserve biodiversity. This statement has been established by several studies in many countries over the world

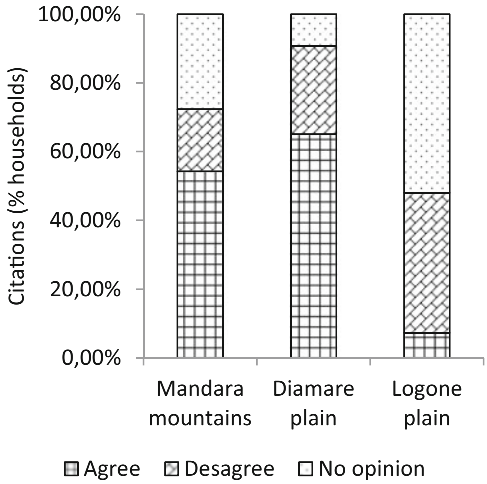

Fig. 6.5 Prospect to increase the potential of trees in farming systems

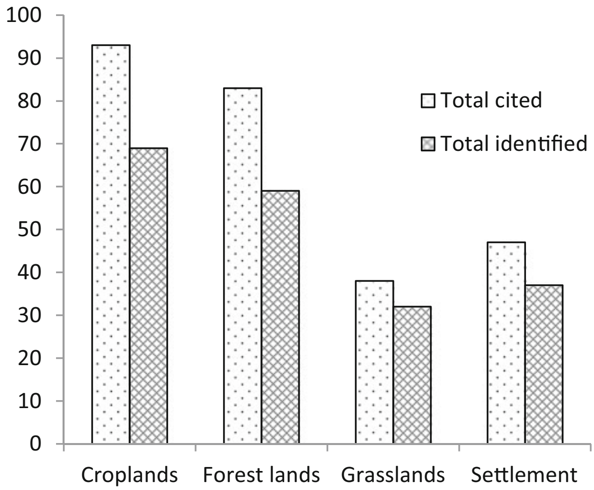

Fig. 6.6 Plant species citations in the main land uses

(Foley et al. 2005; Moreno-Calles et al. 2010). Agroforestry plays five key roles in conserving biodiversity. These include provision of habitat for species with high tolerance of disturbance; safeguarding the germplasm of sensitive species; reduction of the rates of conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems; providing connectivity by creating corridors between habitat remnants which may support the integrity of these remnants and the conservation of area-sensitive floral and faunal species; and providing other ecosystem services such as erosion control and water recharge, thus preventing the degradation and loss of surrounding habitat (Jose 2009; Buck et al. 2004).

At least 95% of smallholder's households affirmed having agroforestry parklands in the Mandara, 80% in Diamare plain and only 30% in Logone plain. Concerning the species richness of these agroforestry parklands, a total of 69 plant species of croplands have been cited by smallholders' farmers in the whole study area and highlight the role of these land uses in biodiversity conservation. Field assessment is needed to confirm this species richness not only at the level of the whole study area but also at the level of each agroforest. However, comparing with other African countries situated within the same ecological area, this species richness is far above 56 plant species identified by Kindt et al. (2008) and Nikiema (2005) respectively in parklands in Mali and Burkina Faso. Of the 69 plant species of these agroforestry parklands, 59 of them are native species, which confirms the fact that multi-strata agroforestry systems cover an intermediate level of plant biodiversity that lies between forests and monocrop perennials or field crops (Swallow and Boffa 2006; Oke and Jamala 2013).

6.8 Land Use and Climate Change

Agroforestry, urban and peri-urban forestry and forest planting offer the opportunity for development of synergies between efforts of climate change mitigation and effort to support vulnerable populations to adapt to the undesirable consequences of climate change (Verchot et al. 2007; Lwasa et al. 2014).

Agroforestry parkland in smallholder agroecosystems of sub-Saharan Africa has a great potential in carbon sequestration through physical and biological processes. Thus, it plays an important role in climate change mitigation (Smith et al. 2008; Luedeling and Neufeldt 2012) through carbon sequestration. Takimoto (2007) shows that agroforestry parkland of West African Sahel has the potential for sequestering more carbon than in treeless land use systems. Furthermore, Smith et al. (2008) estimated at -0.73 to 1.39 Mg C $ha^{-1}year^{-1}$ the potential of carbon sequestration of agroforestry parkland in dryland areas, while Luedeling and Neufeldt (2012) estimated 1.47 Mg CO_2 $ha^{-1}year^{-1}$ in Sahelian parkland. The 69 plant species cited in cropland have a potentiality to mitigate climate change through carbon sequestration. However, the carbon stock potential of agroforestry parklands remains unknown in the semi-arid area of Cameroon. This information could be useful for the REDD+ (reduction of emission of deforestation and forest degradation with sustainable management of forests, conservation of forest carbon stocks and enhancement of forest carbon stocks) project initiators and for the implementation of the National Appropriate Mitigation Action (NAMA) plan.

Carbon sequestration by urban forest and other community-based afforested (A)/ reforested (R) areas of semi-arid area of Cameroon also offers a great opportunity for Clean Development Mechanism (CDM) of the Kyoto Protocol of the United Nations Framework Convention on Climate Change. Agroforestry could also be one of the potential CDM sink projects (Roshetko et al. 2007) if criteria are adequately respected. Some authors indicate that land use systems and agricultural practices which contribute to increase the soil carbon stock could generate carbon offsets

(Hurteau and Brooks 2011; FAO 2000). However, the appropriate agroforestry systems for CDM in semi-arid areas need to be identified.

Urban and peri-urban forestry has also been identified as one of the good approaches to mitigate climate change globally and in African dryland in particular by reducing atmospheric carbon and other urban emissions (Fuwape and Onyekwelu 2010; Lwasa et al. 2014). Urban and peri-urban forestry is well developed in many cities in the Far North of Cameroon. An assessment of small-scale forestry estimated at 75.5 hectares the total area of forest planted by local farmers between 1983 and 2011 with the aim of climate change mitigation and adaptation. A total of 41 plant species were cited as exploited in urban forests. The main cited include *Azadirachta indica*, *Acacia senegal*, *Eucalyptus camaldulensis*, *Khaya senegalensis* and *Senna siamea.* Some of these plant species have been reported as relevant for urban systems in Togo (Raoufou et al. 2011).

According to McPherson et al. (1994), carbon sequestration of urban trees can range from 16 to 360 kg $yr.^{-1}$ respectively for small slow-growing trees with 8–15 cm diameter at breast height and for larger trees growing at their maximum rate. In Cameroon, the capacity of carbon sequestration by urban forest is not well known. However, it has been reported that average carbon sequestration of *Azadirachta indica* is 6372.0 kg C ha^{-1} $year^{-1}$ and *Dalbergia sissoo* 1415.11 kg C ha^{-1} $year^{-1}$ (Shankar et al. 2014).

The sustainable management of these land use can help to avoid deforestation in semi-arid areas of Cameroon and increase their potentials as main carbon sinks.

6.9 Adaptation Options

According to the fifth assessment report of the Intergovernmental Panel on Climate Change, semi-arid areas are among the most vulnerable ecosystems to climate change (IPCC 2013). Many adaptation options including improved tree management and planting through agroforestry, urban and peri-urban forestry, afforestation/ reforestation, etc., can both reduce the negative impacts and take advantage of the positive aspects of changes (Woodfine 2009; UNDP et al. 2009). These land uses are present in study area and constitute an opportunity.

6.10 Conclusion

Many land use systems in semi-arid areas of Cameroon provide some services which are relevant for the livelihoods of the local population. Among these land uses, agroforestry, orchard development, afforestation/reforestation through urban and peri-urban forestry and other forest plantations have been identified as opportunities to combat desertification and enhance climate change mitigation and adaptation and biodiversity conservation. However, the result of this study relies mainly on the perception of local smallholder's farmers. The field assessment of plant resources of these land uses is necessary in order to quantify the capacity of each of these land uses in biodiversity conservation and carbon stock.

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Appendix: Availability of Plant Species in the Land Use Type

N°	Species	Settlement				Grasslands				Cropland				Forest lands			
		T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs
1	*Acacia nilotica*	1	1	1	1	1	0	0	1	0	1	0	1	1	0	0	1
2	*Acacia polyacantha*	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0
3	*Acacia senegal*	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0	0
4	*Acacia seyal*	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
5	*Acacia* sp.	0	1	1	1	0	0	0	0	0	1	0	1	1	1	0	1
6	*Adansonia digitata*	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	1
7	*Anarcadium occidentale*	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
8	*Annona senegalensis*	0	1	1	1	0	0	0	0	0	1	0	1	1	1	0	1
9	*Anogeissus leiocarpus*	0	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1
10	*Asparagopsis* sp.	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
11	*Azadirachta indica*	1	1	1	1	1	0	0	1	1	1	0	1	1	1	0	1
12	*Balanites aegyptiaca*	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1
13	*Bombax costatum*	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
14	*Borassus aetiopium*	1	1	0	1	0	0	0	1	1	1	0	1	1	0	0	1
15	*Boswellia dalzielii*	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
16	*Brachiara* sp.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
17	*Carica papaya*	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
18	*Cassia occidentalis*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
19	*Cassia* sp.	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	*Cissus quadrangularis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
21	*Citrus aurantifolia*	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
22	*Citrus lemon*	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

(continued)

N°	Species	Settlement				Grasslands				Cropland				Forest lands			
		T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs
23	*Citrus* sp.	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
24	*Citus aurentifolia*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
25	*Cochlospermum planchonii*	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
26	*Combretum collinum*	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	1
27	*Combretum glutinosum*	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
28	*Combretum molle*	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
29	*Commiphora kerstingii*	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1
30	*Costus spectabilis*	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1
31	*Crinum* sp.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
32	*Croton gratissimus*	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
33	*Daniellia olivieri*	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
34	*Detarium microcarpum*	0	1	0	1	0	0	0	0	0	1	0	0	1	1	0	1
35	*Dioscorea* sp.	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
36	*Diospyros mespiliformis*	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
37	*Entada africana*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
38	*Eucalyptus camaldulensis*	1	1	0	0	0	0	0	0	0	1	0	1	1	1	0	1
39	*Faidherbia albida*	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1
40	*Ficus glumosa*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
41	*Ficus gnaphalocarpa*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
42	*Ficus platyphylla*	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
43	*Ficus* sp.	1	1	0	1	0	0	0	0	0	0	0	1	0	1	0	1
44	*Ficus sycomorus*	0	0	0	0	1	0	0	0	0	1	0	1	1	1	0	1
45	*Ficus thonningii*	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
46	*Gardenia aquala*	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
47	*Gardenia erubescens*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

48	*Gardenia triacantha*	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
49	*Gossypium* sp.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
50	*Grewia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
51	*Guiera senegalensis*	0	0	0	0	0	1	0	1	1	1	0	1	0	0	0	0
52	*Haematostaphis barteri*	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1
53	*Hexalobus monopetalus*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
54	*Hibiscus cannabinus*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
55	*Hyparrhenia rufa*	1	0	0	0	1	0	1	1	1	0	0	0	1	1	0	1
56	*Hyptis spicifera*	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
57	*Ipomoea* sp.	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
58	*Khaya senegalensis*	0	1	0	0	1	0	0	1	0	1	0	1	1	1	0	1
59	*Lannea fructicosa*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
60	*Lannea schimperi*	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1
61	*Leptadenia hastata*	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1
62	*Leucas martinicensis*	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
63	*Leucena* sp.	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
64	*Mangifera indica*	0	1	1	1	0	0	0	0	0	1	0	1	0	0	0	0
65	*Mitragyna inermis*	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
66	*Moringa oleifera*	0	1	0	1	0	0	0	0	0	1	0	1	1	1	0	1
67	*Nauclea latifolium*	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
68	*Parkia biglobosa*	0	1	0	1	0	0	0	0	0	1	0	1	1	1	0	1
69	*Phoenix dactylifera*	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
70	*Piliostigma reticulatum*	0	0	0	0	1	0	0	1	0	1	0	1	1	1	0	1
71	*Piliostigma thonningii*	0	1	0	1	0	0	0	0	0	1	0	1	1	0	0	0
72	*Psidium guajava*	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0
73	*Ricinus communis*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
74	*Sclerocarya birrea*	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	1

(continued)

N°	Species	Settlement				Grasslands				Cropland				Forest lands			
		T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs	T	FW	F	NTFPs
75	*Senna occidentalis*	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
76	*Senna siamea*	1	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0
77	*Senna singuena*	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1
78	*Senna tora*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
79	*Sesbania pachycarpa*	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1
80	*Sida rhombifolia*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
81	*Sporobolus* sp.	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0
82	*Steganotaenia araliacea*	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1
83	*Stereospermum kunthianum*	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1
84	*Strophantus tomentosus*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
85	*Strychnos spinosa*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
86	*Swartzia madagascariensis*	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
87	*Tacca leonpetaloides*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
88	*Tamarindus indica*	0	1	1	1	1	1	0	1	0	1	0	1	1	1	0	1
89	*Terminalia macroptera*	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1
90	*Terminalia mentali*	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
91	*Terminalia* sp.	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
92	*Vetiveria nigritana*	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0
93	*Vitellaria paradoxa*	0	1	0	1	0	0	0	0	0	1	0	1	1	1	0	1
94	*Vitex doniana*	0	1	0	1	0	0	0	0	0	1	0	1	0	1	1	1
95	*Ximenia americana*	0	1	1	1	0	0	0	0	0	1	0	1	1	1	0	1
96	*Ziziphus mauritiana*	0	1	0	1	0	1	0	0	0	1	0	1	1	1	0	1
97	*Ziziphus spina-christi*	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
	Total	**13**	**28**	**13**	**30**	**18**	**6**	**4**	**26**	**7**	**48**	**2**	**53**	**39**	**41**	**5**	**52**

T timber, *FW* fuel-wood, *F* fodder, *NTFPs* Non-timber forest products

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7 Impacts of Climate Change on Ecosystem Services of Agroforestry Systems in the West African Sahel: A Review

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Abstract

Climate change is expected to affect the livelihoods of rural dwellers as well as the potential provisioning of tree ecosystem services in the West African Sahel. Since the past 100 years, rainfall has declined by 20–30% while the mean temperature increased by up to 1.3 °C in the West African Sahel. Furthermore, there is an uneven spatial and temporal distribution of the rainfall in this area of the West Africa. Better knowledge of the relationship between climate change and tree ecosystem services is necessary for sustainable management of tree ecosystem. The current chapter seeks to address this relationship through a review analysis on the climate change impacts on tree ecosystem services of agroforestry systems. This review shows that there is mounting evidence that climate change impacts the delivery of tree ecosystem services through the erratic rainfall. Therefore, a significant relationship ($r^2 = 0.62$, $n = 45$ years, $p < 0.001$; $r^2 = 0.65$, $n = 20$ years, $p < 0.05$) was found between tree growth and annual rainfall amounts in Mali and Niger, respectively. Then, the consequence of this relationship leads to a reduction of the provision of ecosystem services of agroforestry in the Sahel. The supporting services increase the soil carbon, which is critical for enhanced crop production by ensuring food security in vulnerable zone like the drylands. Policies and promotion of sustainable

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management strategies of tree ecosystems should, therefore, target enhancement of food and nutrition security of the rural populations in the West African Sahel.

Keywords

Drylands · Erratic rainfall · Livelihoods · Sustainable management · Tree ecosystem

7.1 Introduction

The West African Sahel (17°W–23°E and 13°N–17°N) is one of the largest dryland regions in the world (Ben Mohamed et al. 2002) and is vulnerable to environmental stressors and food shortage due to the effects of climate change (Gonzalez et al. 2012). Climate remains the main factor that threatens the livelihoods of rural dwellers in the Sahel region of West Africa. Thus, changes in the climate are likely to strongly affect biodiversity and its ecosystem services, which are the pillars of human well-being. These changes are results of the Intertropical Conversion Zone (ITCZ), which is creating both winds from the ocean and winds from the Sahara region that are more dusty and warmer. The two opposing wind directions cause the annual West African monsoon and, consequently, threaten human well-being over the Sahel.

The fact that climate change affects and continues to affect the subsistence of populations in the Sahel has become a crucial challenge for sustainable development of the region (Mertz et al. 2009; Epule et al. 2017). This challenge is composed of the likely impacts on ecosystem services of agroforestry systems, agricultural production, and livelihoods. Agroforestry systems are traditional land use systems in which trees are integrated in agricultural lands. These systems are widely spread over the Sahel and savanna regions of West Africa and practiced for centuries. However, the West African Sahel region is particularly more vulnerable to climate change impact (Giannini et al. 2005; Reynolds et al. 2007; Epule et al. 2013) due to its dependence on rainfed agriculture. Rural livelihoods in those areas are widely dependent on agriculture and non-timber forest products, which are affected by climate change. For this reason, the areas are no longer able to deliver good yields in ecosystem services to sustain the livelihoods of the rural people.

The temperatures in the Sahel have increased by between 0.1 °C and 2.0 °C (IPCC 2007) while rainfall has declined from the southern to the northern parts of the West African Sahel over the past three decades. Touré et al. (2017) reported an increase of both maximum and minimum temperatures for all the three ecological zones (Sudanian, Sahelian and Sahel-Saharan) in the West African Sahel. In addition, rainfall isohyets in the Sahel have shifted from 1° to 2° of latitude as compared to the wetter conditions during the period between 1930s and 1960s (Nicholson 2013). Consequently, the rainfall in the Sahel has declined by 20–30% during the last twentieth century (Dai et al. 2004; Maranz 2009), while the mean temperature increased by up to 1.3 °C (Hulme et al. 2001). In addition, the mean annual rainfall varies from year to year and decade to decade, which ranges from 350 to 800 mm in the north-south locations (Ben Mohamed et al. 2002). The impacts of the variability of climate hazard, like rising of temperature and decrease in rainfall, resulted in an increase in tree mortality and species richness across the West African Sahel, such as Burkina Faso, Chad, Mali, Mauritania, Niger, Nigeria and Senegal (Gonzalez 2001; Wezel and Lykke 2006; Gonzalez et al. 2012). Therefore, about 50% of the 60 million people living in the Sahel are more vulnerable to food insecurity due to climate change (Verpoorten et al. 2013). This chapter explores the links between tree ecosystem services of agroforestry systems and climate change in the West African Sahel. It describes the tree ecosystem services from agroforestry systems that contribute to mitigation and adaptation to climate change, the patterns of climate change in the Sahel, vulnerability of the human population to climate change, climate change impacts on agroforestry ecosystem services, as well as the rural livelihoods and ecosystem services in the Sahel.

7.2 Tree Ecosystem Services from Agroforestry Systems

The concept of ecosystem services (ES) has been introduced by the Millennium Ecosystem Assessment (MEA) as the benefits people derive from the ecosystem (MEA 2005; Laxmi et al. 2015), which constitute the basis of human livelihood and, hence, are closely related to human well-being (Ouyang et al. 2016). These ecosystems play an important role for economic development (Locatelli et al. 2008). According to the Millennium Ecosystem Assessment (MEA), the ecosystem services are categorized into four groups, namely: provisioning services, regulating services, supporting services, and cultural services (Table 7.1). Provisioning services, such as the supply of charcoal and shade, are well-appreciated by rural farmers because of their direct benefits to the population. They also generate income (trade of charcoal and fuelwood) for rural dwellers, which contributes to increase their resilience to climate change (Lamien et al. 1996; Faye et al. 2010). However, ecosystem services of agroforestry systems (Fig. 7.1) vary according to the system, species composition, age of component species, management practices,

Table 7.1 Typology of ecosystem services[a]

Provisioning services	Charcoal, food, freshwater, bioenergy, fiber, useful molecules, genetic resources, soil, air
Regulating services	Climate regulation, disturbance regulation, hydrological flow regulation, water purification, air purification, disease regulation, erosion control, biological control, pollination, carbon sinks
Supporting services	Soil formation and retention, nutrient cycle, trace element cycle, carbon cycle, primary production, oxygen production, necromass recycling, natural habitats
Cultural services	Inspiration, aesthetics, education, recreation, sense of belonging, cultural, scientific and educational heritage, spiritual benefits

[a]Source: MEA (2005)

Fig. 7.1 Typical agroforestry ecosystem in the West African Sahel dominated by *Vitellaria paradoxa* (key tree species in agroforestry in the West African Sahel), with no natural regeneration, is considered to be highly vulnerable due to the vagaries of climate change

environmental conditions, and geographic location (Jose 2009). For example, the ability of ecosystems to continue providing the services and other functions is mostly determined by environmental factors like climate change (Idinoba et al. 2010).

7.3 Patterns of Climate Change in the West African Sahel

The drylands, like the West African Sahel, are characterized by water scarcity associated with unimodal rainfall pattern (Ali and Lebel 2008), with a brief irregular rainy season and a long intense dry season from October to May. Furthermore, there is an uneven spatial and temporal distribution of the rainfall in the West African Sahel. This rainfall plays an important role in determining agricultural production as well as the economic and well-being of rural communities compared with temperature (Haile 2005; Lobell and Burke 2008). Both rainfall and temperature are characterized by annual variability patterns in the West African Sahel as indicated by the rainfall anomaly index (RAI), which describes the wetness/dryness of rainy seasons. This index is used to assess if the rainy season is wet (RAI range from 0 to 2) or dry (RAI range from −2 to 0) (Ali and Lebel 2008). For the climate data of 50 years (from 1968 to 2017) in the Sudano-Sahelian zone in Mali, 54% of the years were dry (RAI range from −2 to 0) against 46%, which were wet (RAI range from 0 to 2) (Fig. 7.2). It is likely that the pattern is the same for other West African

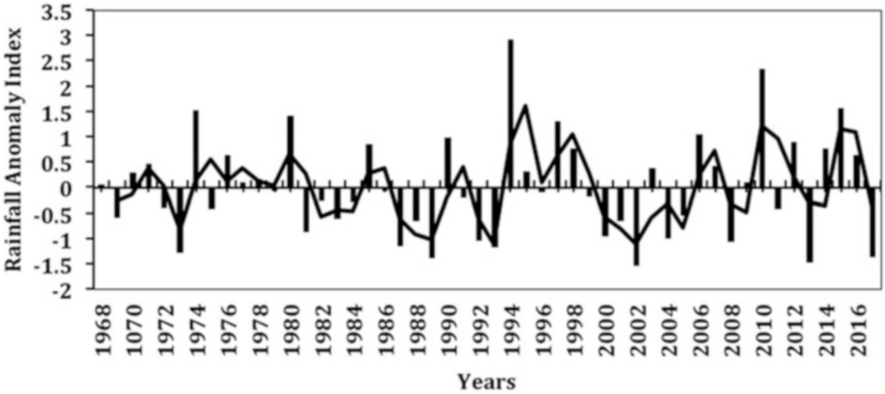

Fig. 7.2 The rainfall precipitation index from 1968 to 2017 in the Sudano-Sahelian zone in Mali

Sahelian countries. This interannual variability of the rainfall impacts on the rural population and on economy of the region.

7.4 Vulnerability of the Human Population to Climate Change

Vulnerability is defined as the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, including climate variability and extremes (Boureima et al. 2012). This vulnerability is a function of the character, magnitude and rate of climate change, as well as variation to which a system is exposed. In the Sahel, vulnerability is expected to have considerable negative impacts particularly on the agricultural sector. Indeed, agriculture is entirely reliant on the limited 3–4 months of variable summer rainfall (June–September), making it highly vulnerable to climate variability and change. For instance, more than 50% of the population in the West African Sahel is employed in the agricultural sector, and this sector contributes in the range of 35 to 60% of the gross domestic product (Dube et al. 2016). Moreover, with low incomes and basic farming technologies, many farmers in the West African Sahel remain expose to climate variability and change. The rural populations in the Sahel are considered one of the most vulnerable on earth (Barbier et al. 2009) due to the fact that the Sahel is subject to frequent drought periods and interannual variability of rainfall is very high. This has significant consequences for the farmers whose incomes depend mainly on rainfed agriculture. Crop failures due to drought as well as to pests and diseases are more recurrent in the last three decades. These challenges are particularly acute in the drylands where land degradation, water stress, current climate variability, and high costs of fertilizers contribute to low crop yields (Zougmoré et al. 2014; Andrieu et al. 2017). Consequently, the rural population experience extreme poverty, recurrent food shortages, and nutrition crises. Nevertheless, the rural communities in the West African Sahel have always managed their resources and livelihoods in the face of changing environmental and socioeconomic conditions (Mertz et al. 2009). They developed adaptation strategies (e.g. use of improved drought-tolerant crop varieties, diversification of crops, off-farm activities, and seasonal migration) to enable them to cope with climate damage (Lacy et al. 2006; Okonya et al. 2013; Sanogo et al. 2017).

7.5 Climate Change Impacts on Agroforestry Ecosystems

In the West African Sahel, the edible fruit species appear far more abundant than non-comestible species in agroforestry systems (Maranz 2009). The most dominant tree species in agroforestry systems are shea tree (*Vitellaria paradoxa*: Sapotaceae), baobab (*Adansonia digitata*: Bombacaceae), locust bean (*Parkia biglobosa*: Fabaceae, subfamily Mimosoideae) and *Faidherbia albida* (Fabaceae, subfamily Caesalpinioideae) (syn. *Acacia albida*: Fabaceae, subfamily Mimosoideae). They are the most preferred by farmers due to their potential economical values (Teklehaimanot 2004; Faye et al. 2010). The climate hazards limiting delivery of ecosystem services are mainly rainfall and temperature, which affect plant growth (Fig. 7.3) and, therefore, their potential to deliver ecosystem services. The evidence is that an increase in temperature and decrease in precipitation are disrupting the ecological functions of ecosystem services (Pedrono et al. 2016). A significant relationship ($r^2 = 0.62$, $n = 45$ years, $p < 0.001$; Fig. 7.3) was found between *V. paradoxa* tree growth and annual rainfall amounts in Mali (Sanogo et al. 2016). Similar results ($r^2 = 0.65$, $n = 20$ years, $p < 0.05$) were reported by Nicolini et al. (2010) for *Vachellia seyal* in Keita Valley, in the Sahelian zone of Niger. As a result, the provision of ecosystem services and the well-being of people that rely on these

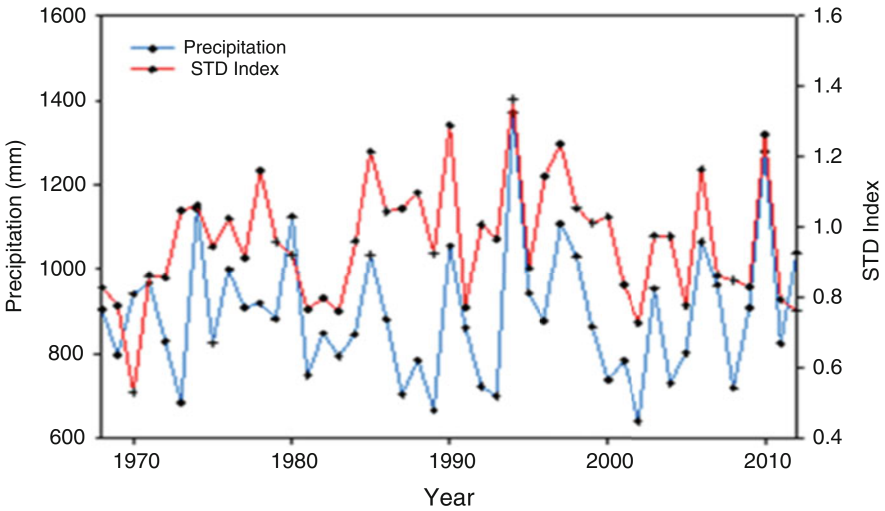

Fig. 7.3 Correlation between *Vitellaria paradoxa* tree growth and precipitation in the Sudano-Sahelian zone in Mali (Sanogo et al. 2016)

services are being modified in the drylands. Idinoba et al. (2010) reported that by 2000, 33.6% of the savanna ecosystem in the dryland were transformed to degraded open cultivated land. In addition, there is mounting evidence that climate change impacts the delivery of tree ecosystem services through the erratic rainfall (Idinoba et al. 2010). In the recent study, two major climate hazards (drought and wind), which could reduce the ecosystem services provided by trees, were reported (Sanogo et al. 2016). It was also emphasized that drought has more detrimental impacts on trees and their ecosystem services whereas wind is responsible for the dropping of flowers, thus reducing fruiting. Despite the multipurpose use of agroforestry, its delivery of ecosystem services is strongly affected by erratic rainfall (Dawson et al. 2011). In the western Sahel, Gonzalez et al. (2012) reported a 20% decline in tree density and a significant decline in species richness across the second half of the twentieth century. Similar results were reported in previous studies over the Sahel, which were attributed to climate change (Kelly et al. 2004; Tappan et al. 2004; Maranz 2009). Consequently, the tree cover in agroforestry ecosystems is only about 5% in the Sahel (Mbow et al. 2014). Moreover, there is a report projecting temperature rise of between 1 °C and 2.75 °C by the year 2030 (Butt et al. 2003), which will alter the growth, and reproduction of trees and, ultimately, the disturbance regimes.

7.6 Rural Livelihoods and Ecosystem Services in the Sahel of West Africa

Rural livelihoods in the Sahel are, fundamentally, dependent on agriculture and ecosystem ecological services. For example, trees in agroforestry systems provide a range of goods and ecosystem services to the population. They have the potential to promote climate resilience through their ecosystem services, which are crucial for the livelihood of rural communities in the Sahel. Maranz et al. (2004) reported that the low annual crop yields are offset by fruit yields from large tree species maintained in agroforestry systems, which have an important nutritional value to balance the starch-based (cereals) diet of that region. Trees enhance carbon stocks (De Zoysa and Inoue 2014) and conserve biodiversity, natural resources as well as their services (Gonzalez et al. 2012; Dhanya et al. 2014). Therefore, tree-based ecosystems play an important role in addressing adaptation to climate change through increased household incomes as a result of products and services, e.g., fruits, butter, shade, firewood, charcoal, medicines, microclimate amelioration, fertilizer, windbreaks, prevention of erosion and habitat for organisms, less evaporation and more soil moisture, and reduced soil temperature (Alander 2004; Faye et al. 2010; Bayala et al. 2014). Furthermore, in the context of erratic rainfall, these ecosystems buffer the harsh climatic conditions by lowering high temperatures and increasing water and air humidity that are beneficial to crops (Hulme et al. 2005; Bayala et al. 2014).

To depict the importance of trees both for adaptation and mitigation, a diagram that describes the regulating, provisioning, and supporting services is presented (Fig. 7.4). For instance, trees in agroforestry systems contribute to the reduction of

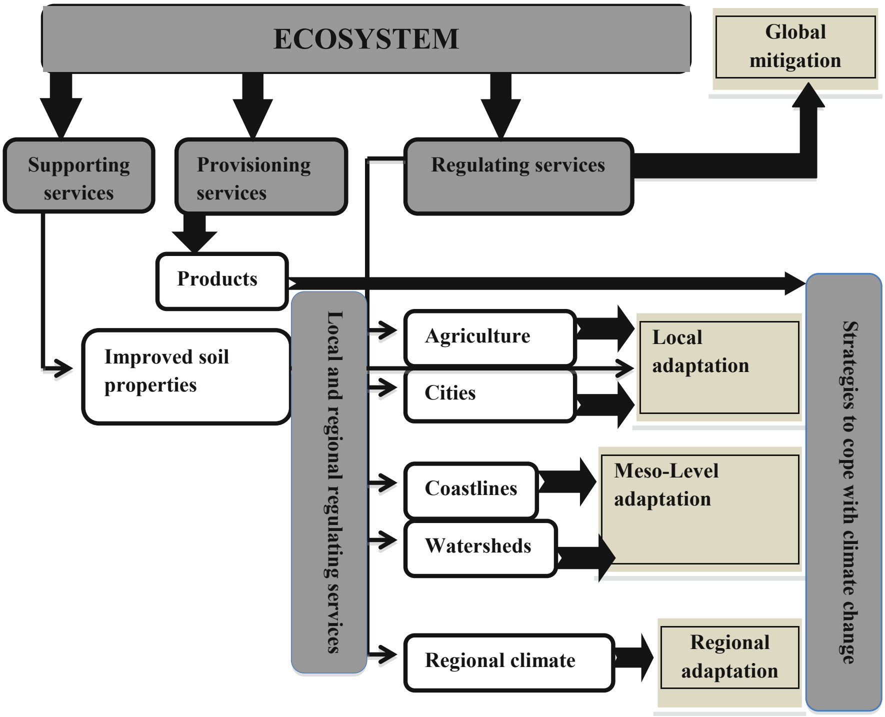

Fig. 7.4 Conceptual framework on contribution of tree ecosystem services to deal with climate change adaptation and mitigation in the West African Sahel

carbon dioxide (supporting services) in the atmosphere by accumulating and storing biomass in the belowground compartment as soil carbon. So, by doing the supporting services increase the soil carbon, which is critical for enhanced crop production in the Sahelian region. Many previous studies related to the role of trees in climate change adaptation reported that ecosystems with trees have higher carbon sequestration potentials than treeless farming systems (De Zoysa and Inoue 2014; Tubiello et al. 2015). Furthermore, Bayala et al. (2006) reported higher soil carbon contents under *P. biglobosa* and *V. paradoxa* than in the open areas in the Sahel. The potential of biomass carbon and total soil C stocks of tree species in agroforestry systems ranged from 0.7 to 54 and 28.7 to 87.3 Mg C ha^{-1}, respectively (Takimoto et al. 2008; Bayala et al. 2014). These processes are important in improving soil properties that will highly contribute to improve food security and human well-being. The products derived from trees (provisioning services) increase food and improve nutrition security in the West African Sahel (Fig. 7.4). The regulating services provided by trees reduce the effects of floods and moderate the effects of climate variations. Ecosystem services, like supporting services, provisioning services, and regulating services, increase the resilience at local and regional levels.

7.7 Conclusions and Outlook

The current paper reviewed the literature about the contribution of trees to addressing both the adaptation to and mitigation of climate change in the West African Sahel. There has been a recent accumulation of evidence that demonstrates the impacts of climate change on tree ecosystem services of agroforestry systems, which support the livelihoods of the population in the Sahel.

This review revealed that trees contribute to the resilience of the local population to climate change through adaptation and mitigation (provision of ecosystem services) and offer habitats for biodiversity conservation. However, it was noted that studies on impacts of climate change on tree ecosystem services are limited in the West African Sahel, and this calls for more investigations. This is required in order to understand how to improve the management of these ecosystems, including a better complementarity between trees and crops. Besides, policies for the preservation of such ecosystem services are also important for improved human well-being.

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8 Agroforestry Systems for Improving Nutrient Recycling and Soil Fertility on Degraded Lands

G. W. Sileshi, P. L. Mafongoya, and Arun Jyoti Nath

Abstract

Land degradation affects about 30% of the total global land area, posing unprecedented social, economic and environmental problems. In total, over 3 billion people reside in areas with some form of land degradation. Many of these are small landholder farmers, who are also at the forefront of land degradation and its consequences. Globally, an estimated 2.2 billion ha of degraded land is potentially available for restoration. Agroforestry, defined as the growing of perennials (trees, shrubs, bamboos and palms) with annual crops and/or livestock on the same piece of land, is believed to reverse land degradation, restore carbon and nutrient stocks and improve soil fertility. However, our knowledge of nutrient cycling in many agroforestry systems on degraded land is still evolving. Therefore, the objective of this review is to provide a synthesis of nutrient cycling and soil fertility improvement through agroforestry practices with a focus on restoring the productivity of degraded lands. The review provided substantial evidence for amelioration of land degradation and creating a more closed nutrient cycling via deep nutrient capture, increased supply via N fixation, litter production and decomposition and increased soil biological activity in agroforestry than in annual cropping systems. Deep capture of nutrients by tree roots can also recycle nutrients leached from inorganic fertilizers applied to crops, thus improving

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nutrient use efficiency and potentially reducing negative environmental consequences. However, agroforestry will not eliminate the need for phosphorus (P) inputs on P-deficient soils. Initial tree establishment on degraded land may be challenging due to soil P deficiencies and water stress. The literature reviewed provides evidence that inoculating tree seedlings with appropriate N-fixing bacteria and mycorrhizal fungi, and application of phosphorus fertilizer ensures better tree establishment. Therefore, we strongly recommend the routine application of these inputs during tree planting in drylands to maximize nutrient cycling.

Keywords

Alley cropping · Biological nitrogen fixation · Fertilizer trees · Improved fallow · Intercropping · Mycorrhizae · Parkland · Shifting cultivation

8.1 Introduction

Land degradation is a physical, chemical and biological process set in motion by activities that reduce the land's inherent productivity. According to the Millennium Ecosystem Assessment (MEA 2005), land degradation is the long-term loss of on-site and off-site terrestrial ecosystem goods and services. The causes of land degradation are inappropriate land use practices including conversion of forests to other land use, logging, shifting agriculture, crop residue removal, overgrazing, intensive mechanized tillage and irrigation (Hillbrand et al. 2017; Tamene et al. 2019). Shifting cultivation (slash-and-burn agriculture) is practised on 280 M ha worldwide (Heinimann et al. 2017) covering large parts of the humid and subhumid tropics. The problem is that shifting cultivation is often practised on fragile, low activity clay soils such as Acrisols, Alisols, Ferralsols, Luvisols and Lixisols, which are common in humid and subhumid tropical regions. Acrisols, Alisols and Ferralsols suffer from soil acidity, aluminium toxicity, low nutrient reserves, nutrient imbalance and multiple nutrient deficiencies (IUSS 2014). Acrisols are also prone to erosion, particularly on exposed sloping land, while Luvisols are extremely susceptible to crusting, compaction and erosion and low moisture retention (IUSS 2014).

In some places, land degradation is manifest by desertification, while in others it is inferred from declining crop yields (Hillbrand et al. 2017). It may also be manifest by invasion of aggressive grasses (e.g. *Imperata cylindrica*) and some ferns, which block natural forest regeneration for decades (Garrity et al. 1997). Such lands are prone to frequent uncontrolled fires, which may increase erosion risks (Pathak et al. 2017). Soil salinization is another major cause of land degradation, the global extent of saline and sodic soils being 831.4 M ha (FAO and ITPS 2015; Gupta and Dagar 2016). The problem of natural salinization, sodication and alkalinization is especially widespread in Central Asia (Toderich et al. 2013), and it is rapidly increasing due to inadequate drainage or use of saline water in agriculture (Khamzina et al. 2009).

The various forms of land degradation altogether affect about 30% of the total global land area across all agroecological zones, and this now poses unprecedented social, economic and environmental problems (Nkonya et al. 2016). In total, over 3 billion people reside in areas with some form of land degradation, but its impact is much greater on poor land users (Nkonya et al. 2016). Many of these lands are managed by poor small landholder farmers, who are also at the forefront of land degradation and its consequences (Antle et al. 2007; Nath et al. 2018). Globally, the annual cost of land degradation on cropland and grazing land alone was estimated to be about US$ 300 billion (Nkonya et al. 2016).

Among the different regions of the world sub-Saharan Africa (SSA) has experienced the most severe land degradation at an alarming rate (FAO and ITPS 2015; Nkonya et al. 2016). Over 95 million hectares of land in SSA has reached such a state of degradation that substantial investment will be needed to make them productive again (Henao and Baanante 2006). Over 77% of the degraded land in SSA occurs in drylands (Dregne and Chou 1992). About 61% of rain-fed croplands, 18% of irrigated lands and 74% of rangelands located in the drylands in SSA are degraded (Dregne and Chou 1992). The annual cost of land degradation is estimated at US$ 65 billion or about 7% of the GDP of the SSA region (Nkonya et al. 2016).

Although land and soil are intrinsically linked, it is very important to make the distinction between land degradation and soil degradation. Land degradation is a multidimensional concept referring to the issues of degradation and sustainability at the landscape level, whereas soil degradation refers to loss of soil quality and function (Escadafal et al. 2015). In that sense, soil degradation is a subset of land degradation. The Global Assessment of Soil Degradation (GLASOD) identified 12 types of soil degradation, namely, water erosion, wind erosion, overblowing, loss of nutrients and/or soil organic matter (SOM), salinization, acidification, pollution, compaction and physical degradation, waterlogging and subsidence of organic soils (FAO and ITPS. 2015). According to the recent assessment by the Intergovernmental Technical Panel on Soils, the most significant threats to soil function at the global scale are soil erosion, loss of soil organic carbon (SOC) and nutrient imbalance (FAO and ITPS 2015).

In many soils, soil organic matter (SOM), which contains roughly 55–60% C by mass, contributes to most of the SOC (FAO and ITPS 2015). In most regions of the world, loss of SOM, nutrient deficiencies, soil acidity and associated toxicities are common problems affecting agriculture (FAO and ITPS 2015). The factors leading to loss of SOM in a system are those that either cause a decrease in plant biomass or those that lead to increased decomposition rates (Bot and Benites 2005). Decreases in biomass and organic matter supply results from clearing forest for agriculture, biomass burning, overgrazing, crop monocultures (especially those with high harvest index), removal of crop residues (FAO and ITPS 2015) and the resultant disappearance of the litter layer, with a consequent reduction in the numbers and variety of soil organisms. Any material harvested for off-site use (e.g. biomass transfer) would also reduce the amount available to maintain soil cover and organic matter. Increased decomposition rates result from repeated tillage and the use of fertilizers. The GLASOD expert survey indicated that the most widespread cause of soil degradation in SSA was water erosion, followed by wind erosion, chemical degradation and physical degradation (FAO and ITPS. 2015). In India alone an estimated 90 M ha of agricultural land is affected by water erosion, 16 M ha by acidification, 14 million ha by flooding, 9 million ha by wind erosion and another 6 million ha by salinity (Nath et al. 2018).

The area of land potentially available for restoration has been estimated at 2.2 billion ha globally (Minnemeyer et al. 2011), of which 1.5 billion ha are best suited to mosaic restoration where forests and trees are combined with other land uses, such as agroforestry (Hillbrand et al. 2017). The Bonn Challenge, a global effort launched in 2011, aimed to restore 150 million hectares of deforested and degraded land by 2020. In 2014, the New York Declaration on Forests raised this target to 350 million hectares by 2030 (Climate Summit 2014). On farmland, planting trees is one of the few feasible ways to reverse some forms of degradation and raise productivity. This is especially the case with fertilizer trees (i.e. nitrogen-fixing tree species used in agroforestry) as they can grow on soils where low levels of available N prevent natural vegetation successions (Sileshi et al. 2014).

Agroforestry, the growing of perennials (trees, shrubs, bamboos and palms) with annual crops and/or livestock on the same piece of land, is believed to reverse land degradation, restore carbon and nutrient stocks and improve soil fertility (Nair 1993; Cooper et al. 1996). Agroforestry systems have special functional attributes that facilitate restoration of nutrient stocks and soil fertility through the increase in soil carbon and nutrients (Sileshi et al. 2014; Bayala et al. 2018). Recent analyses also show that vegetation cover and aboveground biomass has strong positive effects on soil health by increasing SOC and reducing soil erosion (Lohbeck et al. 2017). Through fixation of carbon dioxide (CO_2) by photosynthesis and biological N fixation (BNF), perennials in agroecosystems can improve soil properties (Barrios et al. 2012; Sileshi et al. 2014) and reduce soil erosion and nutrient depletion (Sanchez et al. 1997). They can also reverse land degradation caused by invasive grasses such as *Imperata* (Garrity et al. 1997; Handayani et al. 2012). Using appropriate N-fixing species, agroforestry can also effectively revegetate salt-affected land and mitigate salinization in irrigated drylands (Marcar and Crawford 2004). Although less publicized, bamboo-based agroforestry can play a crucial role in nutrient cycling and rehabilitation of degraded land (Nath et al. 2015).

Nutrient cycling in agroforestry systems has been reviewed comprehensively in various publications (Sanchez and Palm 1996; Lehmann et al. 1999; Nair et al. 1999; Montagnini et al. 2000; Dollinger and Jose 2018). However, the extent to which nutrient cycling occurs in the various agroforestry practices and its value in the management of land degradation and mitigation of greenhouse gases has remained less appreciated among practitioners and policymakers. For example, agroforestry has not been included in the intended nationally determined contributions of most countries party to the 2015 agreement on climate change. Therefore, the objective of this review is to provide a synthesis of nutrient cycling and soil fertility improvement through agroforestry practices with a focus on restoring the productivity of degraded lands. The overall aim of this synthesis is to create awareness among researchers, development agencies and policymakers on the role of agroforestry as countries engage in the Koronivia joint work on agriculture and prepare their nationally determined contributions to the United Nations Framework Convention on Climate Change for the coming years.

8.2 Agroforestry Practices Suitable for Degraded Lands

By the year 2010, more than 43% of all agricultural land was under some variation of agroforestry, and an estimated 1.2 billion people around the world dependent upon agroforestry systems (Zomer et al. 2016). Large areas of agroforestry are found in South America (3.2 million km^2), in sub-Saharan Africa (1.9 million km^2) and Southeast Asia (1.3 million km^2). In most of the agroforestry literature, the role of trees in rehabilitation of degraded land is well-documented, but the use of bamboos is poorly documented. Many of the bamboo species can occupy the same ecological niche as trees (Tewari et al. 2015) and are well suited for rehabilitation of degraded land. For example, in Northeast India, bamboo agroforestry established on a degraded land reduced soil compaction by 10% while increasing soil water holding capacity by 23%, SOC by 61%, total soil N by 36%, available soil P by 26% and exchangeable K^+ by 20% (Nath unpublished). Bamboos have many advantages over trees, including fast growth, ability to grow in relatively poor soils, rapid colonization of disturbed land and versatility of use (Nath et al. 2015; Tewari et al. 2015; Sharma et al. 2018).

A variety of agroforestry practices are used around the world (see Nair 1993, Bhardwaj et al. 2017; Chará et al. 2018), and these can be broadly grouped into sequential and simultaneous systems (Rao et al. 1998).

8.2.1 Sequential Agroforestry Practices

Sequential agroforestry systems are those where the crop and tree components occur at different times, even though both components may have been planted at the same time (Sanchez and Palm 1996). Competition for growth resources is minimal in sequential agroforestry because the peak demands for light, water and nutrients occur at different times for each component. Examples of this type are improved fallows and rotational woodlots.

8.2.1.1 Improved Fallows

Improved fallows involve the rotation (2–3 years) of crops with perennials planted for the rapid replenishment of soil fertility on crop land (Sanchez et al. 1997). The improved fallow concept was developed as an alternative to shifting cultivation and the traditional fallows that take a long time to rehabilitate the soil. Improved fallows have been widely tested in the traditional 'slash and mulch' management practised in humid tropical regions of South America (Barrios and Cobo 2004) and to replenish soil fertility in degraded small-scale farms in sub-Saharan Africa (Buresh and Tian 1998; Mafongoya et al. 2006). Rao et al. (1998) identified two categories of improved fallows: (1) short-duration fallows with fast-growing, leguminous trees or shrubs established primarily to replenish soil fertility and (2) medium- to long-duration fallows with diverse species established for amelioration of degraded and abandoned land. In the first category, legume trees are usually planted with the primary purpose of fixing N as part of a crop-fallow rotation (Sanchez et al. 1997). Because soil degradation occurs rapidly in the humid tropics, longer duration fallows may be required to achieve the desired effect on subsequent crops (Rao et al. 1998; Kang et al. 2007).

The soil ameliorating effect of perennials used in improved fallows varies with the species, fallow duration, residue management after fallow clearing, soil type and climate. Tree species used in improved fallows can be either non-coppicing or coppicing. The commonly used non-coppicing species include *Sesbania* spp., *Tephrosia* spp. and pigeon pea (*Cajanus cajan*). These species do not regrow when cut at the end of the typical 2–4 years of fallow period. After 2–3 years of cropping these species need to be replanted. Commonly used coppicing species belong to the genera *Gliricidia*, *Acacia*, *Vachellia*, *Leucaena*, *Calliandra* and *Flemingia*. The perennials may be planted either in single-species fallows or mixed with woody and herbaceous green manure legumes (Chirwa et al. 2003; Gathumbi et al. 2003; Sileshi et al. 2008a). Short fallows may not substantially improve physical properties of some soils. For example, on an eroded and compacted Luvisols in a humid tropical region of Nigeria, Kang et al. (2007) did not observe significant improvement in soil bulk density with 4-year-old fallows of *Leucaena leucocephala*, *Senna siamea*, *Acacia leptocarpa* and *Acacia auriculiformis*. However, they can reduce soil losses. For example, soil loss was 30–100% lower under rotational fallows than under continuous maize in Zimbabwe (Nyamadzawo et al. 2012).

The key process involved in nutrient cycling in rotational fallows is the incorporation of leguminous biomass from the trees into the soil, root decomposition and the transfer of nutrients to the crops. In eastern Zambia, the mixed-species fallows have been shown to have greater influence on soil biota and N cycling compared to single-species fallow rotations (Chirwa et al. 2003; Sileshi et al. 2008a). Mixing shallow-rooted species with deep-rooted species can enhance the soil-water and nutrient uptake zone within the soil profile. More important, mixing of leguminous species enhances complementarity in above- and belowground resource capture (Gathumbi et al. 2003). For example, the mixture ensures more efficient utilization of subsoil nutrients such as nitrate that is otherwise lost through leaching. By injecting a solution of ^{15}N-labeled ammonium sulphate into soil at 0.15 and 1 m depths Gathumbi et al. (2003) measured N acquisition by *Sesbania* (*Sesbania sesban*), *Crotalaria* (*Crotalaria grahamiana*) and the herbaceous green legume Siratro (*Macroptilium atropurpureum*) in mixed stands in western Kenya. When *Sesbania* and *Crotalaria* were mixed there was more subsoil N uptake by *Sesbania* while *Crotalaria* appeared to source a higher proportion of its N from N fixation and topsoil N uptake (Gathumbi et al. 2003). On a degraded Acrisols in eastern Zambia, leaf biomass in *Gliricidia* + *Sesbania* mixed fallows added 125 kg N ha^{-1} compared with 72 kg N ha^{-1} from sole *Gliricidia* fallow (Chirwa et al. 2003). The fertilizer recommendation for maize in that area is 112 kg N ha^{-1}, slightly lower than the nitrogen input provided by the *Gliricidia* + *Sesbania* fallows.

Nutrient budgets conducted in improved fallows in eastern Zambia showed positive N balance at maize yields of 3–4 Mg ha^{-1} in *Gliricidia*, *Sesbania* and *Tephrosia* fallows (Mafongoya et al. 2006). The nutrients added through leaves and litterfall, which were incorporated after fallows, were the inputs, while the nutrients in maize grain harvested, in maize stover removed and in fuelwood taken away at end of the fallow period were considered as nutrient exports. However, P and K budgets were negative in most cases due to removal of maize stover from the field and limited supply of P and K through tree prunings (Mafongoya et al. 2006). This highlights that it is important to apply inorganic P fertilizer together with prunings to meet crop P requirements.

8.2.1.2 Rotational Woodlots

In the rotational woodlot system, food crops are intercropped with leguminous trees during the first 2–3 years. Then the trees are left to grow and harvested in about the fifth year, and food crops are replanted (Nyadzi et al. 2003; Kimaro et al. 2007). The crops grown following the tree harvest are expected to benefit from improved soil conditions by the woodlot species. As in improved fallows, the main processes involved in nutrient cycling are the incorporation of leguminous green manures into the soil and the transfer of nutrients to crops through prunings, leaf drop and root decomposition.

The best example of this practice is found in Tanzania, where farmers use it to overcome the shortage of wood, avoid deforestation and improve soil fertility (Nyadzi et al. 2006; Kimaro et al. 2007). In semi-arid western Tanzania, rotational woodlots using *Acacia crassicarpa* were shown to retrieve leached N from the subsoil (Nyadzi et al. 2006). The major benefits of rotational woodlots are the added value of wood, improved water availability, C sequestration, better nutrient use efficiency and modest increases in crop yields (Nyadzi et al. 2006).

8.2.2 Simultaneous Agroforestry Practices

Simultaneous agroforestry systems are those where the perennials (e.g. trees, palms, bamboos) and the annual crops grow at the same time and sufficiently close to each other to allow competition for light, water or nutrients (Sanchez and Palm 1996). Competition for growth resources is higher in simultaneous than sequential agroforestry practices. Examples of simultaneous practices include intercropping, alley cropping, contour hedges, parklands, silvipastoral systems and multistrata agroforestry.

8.2.2.1 Contour Hedges

A contour hedge is a horizontal strip of multipurpose trees or bamboos that is used for soil erosion control on sloping lands (Pelleck 1992; Nair 1993). With the increase in human population and declining landholding, cultivation of hillsides is common in many countries. This increases the risk of soil erosion. Trees and bamboos planted as contour hedges can reduce soil losses by erosion through increased infiltration and physical barriers created by roots and leaf litter layer creating good soil cover. For example, on a sloping land (5–9% slope) in southern India, soil losses were 5.1 Mg ha^{-1} year^{-1} from *Leucaena* (*L. leucocephala*) hedgerows compared to 11.9 Mg ha^{-1} year^{-1} from bare fallow plots (Ghosh et al. 1989). Over the long term, the hedges can form terraces on the upper side of the hedge. The perennials, at the same time, provide high-quality fodder, firewood, stakes for climbing beans and mulch material.

8.2.2.2 Alley Cropping

Alley cropping (also called alley farming or hedgerow intercropping) is defined as an agroforestry practice where perennials are grown in rows and arable crops (cereals, legumes or horticultural) or pasture grasses are cultivated in the alleys between the tree rows. This is one of the emerging agroforestry practices in South America, North America (Oelbermann et al. 2004), Europe, Asia and Africa (Kang et al. 1999). In the temperate areas, alley cropping of high-value trees (e.g. timber, fruit or nut bearing) with crop or pasture is one of the more common agroforestry practices.

In the tropics, alley cropping was developed as an alternative to slash-and-burn agriculture, for erosion control on sloping land, and amelioration of degraded soils (Kang et al. 1999). One of the key benefits of alley cropping is the control of soil erosion. In a study on a hill slope in the Philippines, soil erosion rates were 5 Mg ha^{-1} year^{-1} in alley cropping compared to 100–200 Mg ha^{-1} year^{-1} in the farmers' practice (Paningbatan et al. 1995).

The woody species are periodically pruned, and their biomass is applied either as mulch or incorporated into the soil (Kang et al. 1999). Depending on the soil type and tree species, the prunings from hedgerows recycle large quantities of plant nutrients. For example, higher nutrient yields were recorded in *Gliricidia* and *Leucaena* on a degraded Luvisols (Alfisol) than on a degraded Arenosols (Entisols) in Nigeria (Kang et al. 1984).

On a dry tropical savanna site in Kenya, alley cropping of sorghum with *Vachellia* (*Acacia*) *saligna* provided a higher internal nutrient cycling than the monocultures of sorghum or pure *Vachellia* stands (Lehmann et al. 1999). However, if all above-ground biomass was exported, the nutrient balance was negative for N, P and K and positive for Ca and Mg (Lehmann et al. 1999). Therefore, for a positive balance of N, P and K, it is necessary to return nutrients through mulching of part of the harvested biomass (Lehmann et al. 1999).

8.2.2.3 Intercropping

A common form of intercropping involves planting annual crops between scattered trees and palms such as coconut palm (*Cocos nucifera*), areca palm (*Areca catechu*) and oil palm (*Elaeis guineensis*). According to estimates by Nair (1993), the area under intercropping with coconut alone is over 6 M ha globally. Over 75% of this area is managed by smallholder farmers in the Philippines, Indonesia and India. Another example of intercropping involves growing annual crops under scattered tree of species such as *Alnus* (*Alnus acuminate*), silver oak (*Grevillea robusta*) and *Markhamia lutea* in the humid tropical highlands of Rwanda and Kenya (Ndoli et al. 2017). Recent analyses by Ndoli et al. (2017) show that larger N input from *Alnus nepalensis* (N-fixing tree) could compensate for yield loss caused by shading in about 60% of the seasons. The findings also suggest that adequate pruning and high leaf litter recycling can reduce the negative effect of shade in low-intensity farming systems (Ndoli et al. 2017).

Another form of intercropping commonly practised in southern Africa combines the elements of rotational fallows and intercropping (Sileshi and Mafongoya 2007). Pure stands of N-fixing species are normally planted in narrow spacing to allow planting annual crops, and the fallows are left to grow for 2–3 years. At the end of the fallow period, the trees are cut, and the leaves and twigs are incorporated into the soil with a hand hoe. During the crop phase, the re-sprouting twigs are cut and the coppice biomass (also called prunings) is incorporated into the soil. A cereal crop, usually maize, is planted between the tree stumps. The addition of prunings and crop residues (e.g. maize stover) recycles nutrients within the soil-plant systems. However, the true additions of nutrients to system come from BNF and deep capture. This practice has been widely tested in Zambia and Malawi (Mafongoya et al. 2006; Akinnifesi et al. 2010). In the intercropping system, *Gliricidia* was reported to provide a safety net function to reduce nitrate leaching. The fact that trees in the intercropping systems transfer nutrients to associated crop plants has been widely demonstrated by empirical studies (Mafongoya et al. 2006; Akinnifesi et al. 2010).

8.2.2.4 Parkland Agroforestry

Parkland agroforestry is common in the semi-arid and subhumid tropics in Africa (Boffa 1999; Bayala et al. 2014), the Mediterranean Europe where it is known as *dehesa* in Spanish or *montado* in Portuguese (Gallardo et al. 2000). In the West African Sahel and parts of Eastern and Southern Africa, parkland agroforestry involves a mix of perennial species such as Faidherbia (*Faidherbia albida*), *Vachellia* (formerly *Acacia*) spp., *Parkia biglobosa* and *Vitellaria paradoxa* under which sorghum, millet, groundnut and sesame are grown (Boffa 1999). Livestock form a significant component of these farming systems, and hence the parklands are typical agrosilvipastoral systems (Boffa 1999). Perennials in the agroforestry parklands in Africa are rarely planted but are derived from natural regeneration and are managed on agricultural land by farmers (Bayala et al. 2012, 2014). This process is called farmer-managed natural regeneration (FMNR) or assisted natural regeneration of trees (Shono et al. 2007; Haglund et al. 2011; Reij and Garrity 2016). In some countries such as Mali, parklands occupy up to 90% of the agricultural land

and support livelihoods of over 2.5 million people (Boffa 1999). Mature trees in the parklands have always been associated with island of high fertility (Sileshi 2016; Bayala et al. 2018). The fact that trees transfer nutrients to associated crop plants is supported by the widespread observations of higher crop yields under Faidherbia canopies than outside the canopy (Sileshi 2016).

8.2.2.5 Silvopastoral System

A silvopastoral system is a land use system in which perennials are integral part of pasture land. Silvopastoral systems cover 9.2 million ha in Central America alone (IAASTD 2008). In grazing systems, livestock graze on pasture under widely spaced or scattered trees (Chará et al. 2018). In the more extensive grazing areas of South America, Asia, Australia and Africa, trees are increasingly being planted in association with improved grasses to increase carrying capacity and/or enhance the productivity of grazing cattle. In high elevation areas of Central America and the Andean region, *Alnus* spp. are prominent components of such systems. For example, in Costa Rica, *Alnus acuminata* stands in pasture grasses occupy over 50,000 ha (Kass et al. 1997), while the espinales of Chile, Bolivia and Argentina are dominated by *Acacia caven* covering over 2 M ha (Muñoz et al. 2007). Similarly, in the overgrazed, semi-arid Chaco of Argentina, Bolivia and Paraguay covering over 1.2 million km^2 (Abril and Bucher 2001; Muñoz et al. 2007) trees in the genera *Vachellia* (formerly *Acacia*), *Leucaena*, *Mimosa*, *Prosopis*, *Pithecellobium* and *Sesbania* provide N for grass growth and browse.

In the more intensively managed areas in Brazil, Venezuela, Colombia, Mexico and parts of Central America and the Caribbean, trees such as *Leucaena* (*Leucaena leucocephala*) are planted in pasture. Similarly, in Southeast Asia, *Leucaena* and *Gliricidia* are widely used in silvopastures. In Indonesia alone, *Leucaena* in pasture land covers >79,000 ha (Shelton et al. 2005). In Australia, hedgerows of *Leucaena* are planted in pasture to provide valuable forage for large-scale beef production. In Queensland alone over 100,000 ha of land is under this management (Shelton et al. 2005). In Western Australia, tagasaste (*Chamaecytisus proliferus*) is grown in wide-spaced alleys or dense plantations (>50,000 ha) both to provide fodder and to reduce salinity by lowering the water table.

8.2.2.6 Multistrata Agroforestry

Multistrata agroforestry comprises tree crop-based land use systems that have two or more vegetation layers ranging from plantations of coffee (*Coffea* spp.), cacao (*Theobroma cacao*) or tea (*Camellia sinensis*) mixed with shade trees to highly diversified systems such as homegardens and agroforests (Scroth et al. 2001). In the humid tropics, trees in the genera *Acacia*, *Albizia*, *Alnus*, *Entada*, *Erythrina*, *Gliricidia*, *Inga*, *Leucaena* and *Millettia* are commonly used in cacao and coffee plantations (Beer et al. 1998; Oelbermann et al. 2004). Globally, cocoa agroforestry systems alone cover 7.8 million ha (IAASTD 2008). Cardamom (*Amomum subulatum*), the most important perennial cash crop in the eastern Himalayas is cultivated predominantly under *Alnus nepalensis* (Sharma et al. 2002; Russo 2005).

Depending on species, the shade tree can be regularly pruned for soil improvement or left to grow fully to produce firewood and timber.

Tropical homegardens are the most complex of the multistrata agroforestry practices (Nair 1993). In the homegardens, intensive mixed intercropping is practised throughout the year. This involves the integration of perennials with food, cash crops and livestock simultaneously on the same unit of land. On an average sized farm (0.2–1.2 ha) over a hundred different plant species can be found, making this system highly integrated. Vertically, 2–4 relatively distinct canopy layers can be recognized (Nair 1993). Bamboos form an important component in the traditional homegardens in the humid zones of north-east India (Tewari et al. 2015).

8.3 Nutrient Cycling and Budget in Agroforestry Systems

8.3.1 Definitions

8.3.1.1 Nutrient Cycling

Nutrient cycling refers to the continuous transfer of nutrients already in the soil plant system from one component to another (Nair et al. 1999; Sanchez and Palm 1996). The perennials in agroforestry can provide nutrient inputs to crops by capturing nutrients from atmospheric deposition, biological nitrogen fixation (BNF) and deep capture and storing them in their biomass (Sanchez et al. 1997). Nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulphur (S) and micronutrients are absorbed by tree roots and returned to the soil via the decomposition of litter and roots (Sanchez and Palm 1996). Perennials in the systems can also increase the availability of nutrients in the soil through the conversion of nutrients to more labile forms of SOM. They enhance SOM both through production of SOM and reducing losses due to erosion. The addition of tree litter, root decay, green manures, crop residues (and animal manure in silvopastoral systems) and their subsequent decomposition results in the formation of organic forms of soil N and P (Sanchez et al. 1997). During decomposition, the organic forms of nutrients in the plant biomass are converted into inorganic forms in the soil solution (e.g. nitrates and orthophosphate ions), which can be readily absorbed by the growing plants. Nutrient cycling in agroforestry systems is expected to be more complex than in agricultural systems because the interactions between trees, crops, symbiotic microorganisms (e.g. nitrogen-fixing bacteria, mycorrhizal fungi) and other rhizosphere microorganisms and soil fauna are an integral part of the belowground complexity in the former. Nutrient cycling in agroforestry systems falls between the 'closed' cycling observed in forest ecosystems and the 'open' cycling in agricultural systems (Nair et al. 1999).

The cycling of nutrients in a terrestrial ecosystem involves an external and an internal cycle (Singh et al. 2014). The external cycle comprises the input and output of nutrients from the ecosystems. For example, biological nitrogen fixation (BNF) constitutes an important process of N input in agroforestry systems (Peoples and Crasswell 1992; Obertello et al. 2003; Russo 2005; Franche et al. 2009). The intersystem nutrient cycle describes those processes responsible for the conversion of the nutrient from one chemical form into another or transfers it between ecosystem pools (Singh et al. 2014). These processes include plant assimilation of nutrients, return of nutrients to soil in litterfall and other organic inputs, litter decomposition, deep nutrient capture (Nair et al. 1999) and nutrient losses through leaching and soil erosion (Sileshi et al. 2014).

8.3.1.2 Nutrient Budgets

Nutrient budgets (or nutrient balances) have been a valuable tool for facilitating the understanding of nutrient cycling in agroecosystems. They can also provide indicators of sustainability that are easy to understand by practitioners and policymakers (Onema et al. 2003). For example, nutrient deficits (negative budgets) indicate declining soil fertility, while surpluses (positive budget) can be used as an indicator of risks of nutrient loss and polluting soil, water or air (OECD 2019). A build-up of surplus nutrients in excess of immediate crop needs can lead to nutrient losses, representing not only a possible cause of economic inefficiency but also a source of potential harm to the environment, through water or air pollution, notably ammonia or greenhouse gas emissions. This indicator is often used for N and P, measured in kg ha^{-1} of agricultural land (OECD 2019).

Nutrient budgets summarize nutrient inputs and outputs from a defined system over a defined period of time. Onema et al. (2003) identified three types of nutrient budgets: farm gate, soil surface and soil system budgets. However, the soil system budget is the most detailed budget, which provides requisite information for nutrient management. Soil system budgets account for nutrient inputs and outputs, recycling of nutrients within the system, nutrient loss pathways and changes in soil nutrient pools (Onema et al. 2003). Inputs into agroforestry system may come through fertilizer, rain, dust, organic materials from outside, N fixation and weathering of rocks. Outputs result from erosion, leaching, crop offtake, denitrification, volatilization of N and burning (Sanchez et al. 1997; Nair et al. 1999). However, our knowledge of nutrient budgets and cycling in many agroforestry systems is still evolving.

8.3.2 Processes of Nutrient Cycling in Agroforestry Systems

Based on our current knowledge, there are at least four broad processes that determine nutrient cycling in agroforestry systems: (1) biological N fixation (BNF), (2) biomass production and decomposition, (3) deep nutrient capture (Nair et al. 1999) and (4) reduction of nutrient losses through erosion (Sileshi et al. 2014). A fifth, but less understood, process involves nutrient inputs through insects and birds that live in the trees and domestic animal (through dung and urine). The key processes will be briefly described below.

8.3.2.1 Biological Nitrogen Fixation

One of the main inputs of N in agroforestry systems is biological nitrogen fixation (BNF). The role of N-fixing species in the rehabilitation of soil in drylands with low fertility and high salinity has been widely documented (Peoples and Crasswell 1992). There are two major symbiotic N-fixing systems, namely, the *Rhizobia*-legume and *Frankia*-non-legume symbioses. Leguminous plant species belonging to over 340 genera fix atmospheric N through symbiotic associations with *Rhizobia*. Non-leguminous perennials belonging to 200 species in eight families of flowering plants are also capable of fixing N through their association with *Frankia* (Obertello et al. 2003; Russo 2005; Franche et al. 2009). Although the amount of N derived from atmosphere and the amount fixed by tree species varies, it is comparable with those reported for common bean, soybean, groundnuts and herbaceous pasture and fodder (Table 8.1; Herridge et al. 2008). The N fertilizer equivalent of the amount of N fixed by trees is in the range of 20–120 kg N ha^{-1}. N fixation rates in *Frankia*-non-legume symbioses are also comparable to those found in legume-*Rhizobium* symbioses (Obertello et al. 2003; Franche et al. 2009). Depending on stand age, density and site conditions, the annual input of N from *Frankia*-non-legume symbioses varies from 43 to 60 kg N ha^{-1} in *Casuarina* spp. and 20–300 kg N ha^{-1} in *Alnus* spp. In *Alnus nepalensis*, for example, annual N fixation increased from

Table 8.1 Amounts of N fixed and contributions to soil fertility by trees

Tree legume	N fixation (%)	Amount of N fixed (kg N ha^{-1})	Fertilizer equivalent (kg N ha^{-1})	Reference[a]
Leucaena leucocephala	35–95	76–274	45–90	1
Leucaena collinsii	32–75	30–330	30–80	2,4
Leucaena pallida	11–67	20–250	20–60	2,4
Leucaena diversifolia	35–65	38–180	20–60	2,4
Gliricidia sepium	26–89	170–204	45–100	1,2,4
Calliandra calothyrsus	29–87	69–377	30–60	1,2,4
Cajanus cajan	84	97	20–82	3
Acacia angustissima	30–75	100–350	69–80	2,3,4
Sesbania sesban	84	84–220	38–120	3
Tephrosia vogelii	–	127	40–60	4
Tephrosia candida	–	280	40–120	4

[a]1. Giller et al. (1997); 2. Mafongoya, unpublished; 3. Chikowo et al. (2004); 4. Mafongoya et al. (2006)

52 kg ha^{-1} in 5-year-old stands, peaking at 155 kg ha^{-1} in 15-year-old stands, and then decreased to 59 kg ha^{-1} in 40-year-old plantations (Sharma et al. 2002).

Among those that are associated with *Rhizobia*, annual N inputs are estimated at 0.5–210 kg N ha^{-1} in *Acacia* spp., 9–161 kg N ha^{-1} in pigeon pea (*Cajanus cajan*), 8–390 kg N ha^{-1} in *Chamaecytisus*, 108–212 kg N ha^{-1} in *Gliricidia*, 99–546 kg N ha^{-1} in *Leucaena* spp., 43–581 kg N ha^{-1} in *Sesbania* spp. and 157–280 kg N ha^{-1} in *Tephrosia* (Table 8.1). However, this widely varies with provenances and stand age. In some species such as Faidherbia, N fixation has not been demonstrated in the field. However, the high N content of the pod and accumulation of soil N under the tree canopy suggests that N fixation does take place in this species (Weil and Mughogo 1993).

Significant amounts of the fixed N are transferred to associated crops. For example, 32–58% of the total N in alley-cropped maize came from N fixed by the adjacent Alnus trees (Jose et al. 2004). Similarly, in coffee agroforestry roughly 30% of the N effectively fixed by *Leucaena*, *Calliandra* and *Erythrina* was transferred to the associated coffee trees (Snoeck et al. 2000). In Sri Lanka, up to 21% of N in grass was derived from transfer of N fixed by *Gliricidia* and *Leucaena* (Jayasundara et al. 1997).

There are many studies demonstrating that prunings and litter from N-fixing trees can be used as a source of N to annual crops (see review in Sileshi et al. 2014). The N contribution to crops is commonly in the range of 40–70 kg ha^{-1} per year. This represents 10–30% of nitrogen applied as prunings. However, N recovery rates reported in the literature are in the range of 10–30% (Sileshi et al. 2014). The low recovery rate is partly caused by lack of synchrony between the N release and N demand by the associated crop. The N not taken up by the associated crop is immobilized in SOM, assimilated by trees (Vanlauwe et al. 1998) or lost from the system through denitrification, volatilization or by leaching.

8.3.2.2 Litter Production and Decomposition

One of the key processes by which perennials in agroforestry systems increase nutrient availability is through production of biomass, input of litter into soil and subsequent decomposition. The decomposition of organic residues from trees and bamboos (leaf litter, prunings, roots) recycles substantial amounts of nutrients depending on the quantity, nutrient content and the decomposition rate of the litter (Nair et al. 1999). Mulching or incorporation of biomass from perennials not only supplies nutrients to the associated crop but it also modifies the soil environment for soil biota and for plants, thus improving nutrient use efficiency (Sileshi et al. 2008a).

Several studies have reported the nutrient content and quantity of biomass produced by perennials, and this has been synthesized in number of reviews (e.g. Nair et al. 1999; Palm et al. 2001; Barrios et al. 2012; Sileshi et al. 2014). Here, we will review only a few as examples to highlight variability in nutrient inputs due to site conditions, species and management. On three sites across a soil fertility gradient in eastern Zambia, we recorded annual litterfall of 0.3–-2.3 Mg ha^{-1} year^{-1}, the highest being from *Calliandra calothyrsus* on a nutrient-poor site (Table 8.2). In another study on three sites in eastern Zambia, Sileshi and

Table 8.2 Litter production (Mg h^{-1} $year^{-1}$) by leguminous trees grown on different sites with soil fertility levels in eastern Zambia

Species	Chadiza (Poor site)	Kalunga (Intermediate)	Kalichero (Fertile site)
Calliandra calothyrsus	1.9	2.3	1.3
Leucaena collinsii	1.4	1.5	0.9
Leucaena pallida	1.3	0.7	0.8
Leucaena diversifolia	0.9	0.7	0.8
Leucaena esculenta	0.5	1.3	0.9
Acacia angustissima	0.5	2.3	1.2
Gliricidia sepium	0.3	1.3	1.7

Source: Mafongoya (unpublished)

Mafongoya (2007) recorded cumulative litter biomass of 3–6 Mg ha^{-1} during the 3-year fallow phase and 1.3–6 Mg ha^{-1} $year^{-1}$ of pruning biomass during the intercropping phase with various legumes.

In the tropical hillsides of Colombia, a *Calliandra* (*Calliandra calothyrsus*) and *Indigofera* (*Indigofera constricta*) improved fallow accumulated 23 Mg ha^{-1} of leaf biomass in 27 months, compared to only 6–18 Mg ha^{-1} in a natural vegetation fallow. The nutrient accumulated in leaf biomass in *Calliandra* fallows was estimated at 308–312 kg N ha^{-1}, 18–24 kg P ha^{-1}, 170–191 kg K ha^{-1}, 99–109 kg Ca ha^{-1} and 40–44 kg Mg ha^{-1} (Barrios and Cobo 2004). In the case of *Indigofera* improved fallows, the nutrient accumulation was estimated at 294–312 kg N ha^{-1}, 22–28 kg P ha^{-1}, 200–208 kg K ha^{-1}, 125–161 kg Ca ha^{-1} and 54–59 kg Mg ha^{-1} (Barrios and Cobo 2004). In *Gliricidia*-maize-pigeon pea intercropping in southern Malawi 191–302 kg N ha^{-1} $year^{-1}$ could be realized from *Gliricidia* prunings alone (Akinnifesi et al. 2010). These studies reveal considerable variation in the amount of biomass produced and the nutrient contents. Like tree species, bamboos produce significant amounts of leaf litter biomass. In *Dendrocalamus strictus* stands in India, Tripathy and Singh (1994) recorded litterfall of 2.7 Mg ha^{-1} $year^{-1}$ from standing biomass of 35 Mg ha^{-1} with annual nutrient return of 28 kg N ha^{-1}, 1.3 kg P ha^{-1} and 12 kg K ha^{-1}. Similarly, in north-eastern India, Nath recorded average litterfall of 0.1–4 Mg ha^{-1} $year^{-1}$ over a growth period of 10 years (Nath unpublished).

The extent of soil fertility improvement through nutrient cycling via litterfall and prunings from trees and bamboos depends on many biotic and abiotic factors. One of the important determinants of decomposition rates is the litter quality indexed by the N to polyphenol + lignin ratio (Mafongoya et al. 1997). Leaves with high N, low lignin and polyphenols such as those of *Gliricidia* and *Sesbania* spp. decompose quickly and release a large proportion of their N (Mafongoya et al. 1997). On the other hand, highly lignified leaves such as those of *Flemingia macrophylla* decompose slowly and may cause immobilization of soil N for several weeks after they are added to the soil. The decomposition pattern of biomass of species with high N and polyphenol contents may be governed by the protein-binding capacity of the polyphenols. Decomposition will be rapid when protein-binding capacity is low as in *Leucaena leucocephala* compared to those with high protein-binding capacity such as *Calliandra* (Mafongoya et al. 1997).

Tree biomass especially from leguminous species supplies substantial amounts of N and K to associated crops. Akinnifesi et al. (2010) provide estimates of annual inputs of N, P and K (kg ha^{-1}) from biomass of some leguminous trees used in improved fallows and intercropping in southern Africa. Generally, the quantity of P contained in the biomass of most perennials used in agroforestry systems is insufficient to supply the associated crop's P demand (Palm et al. 2001).

The quantity and quality of litter and pruning biomass can determine the SOM and hence food availability to decomposer communities in the soil (Sileshi and Mafongoya 2007). SOM includes an infinite number of organic compounds varying from easily mineralizable, simple organic residues to complex, recalcitrant products and microbial biomass. This can contribute to the SOC pool. Even small changes in SOC stocks can have a dramatic impact on land productivity as well as the global C cycle and climate change. According to a recent meta-analysis (Bayala et al. 2018), average increases in SOC were 20.6% in alley cropping, 22.8% in improved fallows and 35.5% in parkland agroforestry over crop monocultures across SSA. In a five-year-old *Leucaena* (*L. leucocephala*) alley cropping, Kang et al. (1999) reported 59–108% increase in SOC in the 0–5 cm soil depth over maize monoculture. After 11 years of continuous cropping, plots alley cropped with *Leucaena* had 16–18% higher SOC than the monoculture maize plots (Kang et al. 1999). In the same experiment plot alley cropped with *Gliricidia* had 9–18% higher SOC than the monoculture maize plots (Kang et al. 1999). In *Gliricidia*-maize intercropping in Malawi, SOM was 12% higher than in monoculture maize after 14 years (Beedy et al. 2010). Similarly, under cacao/*Erythrina* SOC increased by 21% over a 10-year period (Fassbender et al. 1991). In a meta-analysis of studies on *Faidherbia albida* agroforestry parklands across Africa, Sileshi (2016) found 46% higher SOC under trees than in open areas. In India, Brahma et al. (2017) reported that *Piper betle* slash-and-mulch agroforestry established on degraded forest land increased SOC by 22.3 Mg ha^{-1}, and SOC stocks by 115.9 Mg ha^{-1}, representing an increment of 0.74 Mg ha^{-1} year^{-1} (Brahma et al. 2017).

8.3.2.3 Deep Nutrient Capture

Deep nutrient capture is the uptake of nutrients by tree roots from soil depths beyond the reach of crop roots (Sanchez and Palm 1996). This is favoured when perennials are deep rooting and have high demand for nutrients, when water or nutrient stress occurs in the surface soils and/or when extractable nutrients or weatherable minerals occur in the subsoil (Buresh and Tian 1998). These nutrients become an input on being transferred to the surface soil via tree prunings and litter decomposition.

On N-deficient Nitisols in western Kenya, Hartemink et al. (1996) detected nitrate levels in the order of 120 kg N ha^{-1} in the 50–200 cm soil depths. The authors also found that Sesbania fallows depleted this pool, thus capturing a resource that was unavailable to a sole maize crop (Hartemink et al. 1996). Other nutrients which may be captured by the trees include Ca, Mg and K. The deep capture of P is likely to be negligible because of the very low concentrations of available P in the subsoil (Sanchez and Palm 1996). In rotational woodlots in Tanzania, *Acacia crassicarpa*, *Acacia julifera*, *Acacia leptocarpa*, *Leucaena pallida* and *Senna siamea* were able to retrieve inorganic N from up to 2 m deep soil horizons and increase its concentration close to their trunks (Nyadzi et al. 2003).

Generally, intercropping achieves long-term efficiency of nutrient use in deep soils compared to rotational fallows (Mafongoya et al. 2006). This is because in the rotational systems, there is no active perennial legume, and hence nitrate can leach below the effective rooting depth of cereals. In eastern Zambia *Gliricidia*-maize intercropping was more effective for pumping of soil nutrients than a Sesbania-maize rotation because the *Gliricidia* roots remain active in capturing nutrients from the subsoil (Mafongoya et al. 2006).

8.3.2.4 Nutrient Loss in Leaching and Soil Erosion

Leaching is the downward movement of dissolved nutrients in the soil profile with percolating water, and this uncouples N cycling and will result in soil acidification. In humid tropical conditions, nitrate leaching can be considerable. In alley cropping on a sandy Acrisols in the Benin, Sanchez et al. (1997) cite a study reporting lower nitrate leaching under *Leucaena* hedgerows than the no-tree control.

Soil erosion is one of the most pervasive features of land degradation (FAO and ITPS 2015). Water erosion is particularly widespread in mountainous humid tropical and subtropical agricultural landscapes due to heavy rainfall (Labrière et al. 2015). For example, in the East African highlands the prevalence of erosion is very high, affecting 67–99% of the farms (Lohbeck et al. 2017). Global soil erosion rates by water erosion of up to 20–30 Giga (10^9) tonnes ha^{-1} $year^{-1}$ have been recently reported where close to 20–25% results from tillage-induced erosion (FAO and ITPS 2015). Practices that lead to soil erosion include clearing of vegetation, overgrazing, cropping on steep slopes, deep ploughing and leaving crop fields with no ground cover (Hillbrand et al. 2017). Soil erosion carries with it a large amount of N and base cations (Wong et al. 2002).

A recent systematic review (Labrière et al. 2015) revealed that soil erosion in the humid tropics is concentrated in space (over landscape elements of bare soil) and time (e.g. during crop rotation). According to Labrière et al. (2015) soil loss was three times more on croplands than in tree-dominated agrosystems and 99% less under tree crops with contact cover (e.g. grass or cover crop) than tree crops without contact cover. Complex agroforests had three times less soil loss than simple agroforestry system (Labrière et al. 2015).

Trees and bamboos may reduce nutrient losses through erosion and leaching and form a 'safety net' under the root zone of the annual crop (Lehmann et al. 1999). Bamboo is good a soil binder due to their peculiar clump formation and fibrous root system and hence plays an important role in soil and water conservation. Substantial evidence exists that agroforestry practices can reduce nutrient leaching in comparison to sole cropping systems. For example, in Northern Kenya Lehmann et al. (1999) found 53% lower leaching losses of N in alley cropping of sorghum with *Acacia saligna* than sorghum monoculture. This was attributed to a higher root abundance and a higher ratio of nutrient uptake to leaching in the alley cropping than in the monocultures (Lehmann et al. 1999).

8.3.2.5 Nutrient Inputs by Fauna and Microorganisms

Perennials in agroecosystems attract a variety of fauna and microorganisms, which contribute to the soil nutrient pool. Soil enrichment through insect and bird droppings may contribute to soil nutrient inputs. Perennials generally increase the abundance, biomass and diversity of soil fauna depending on the inputs (Barrios et al. 2012). Cumulative litterfall, tree leaf biomass, and re-sprouted biomass under legume species appeared to explain the variation in macrofauna densities (Sileshi and Mafongoya 2007).

Perennials have also been shown to modify populations of microflora and microbial biomass. The microbial communities directly affect soil fertility by carrying out essential processes that contribute to nutrient cycling. Aboveground and belowground organic inputs provide C substrates and nutrients needed for the soil organisms involved in C transformations and nutrient cycling. The mineralization of N and P in soils involves a sequence of processes for which the living microbial biomass provides the enzymes and dead microbial material forms much of the substrate (Read and Perez-Moreno 2003). The microbial biomass becomes part of the active SOM pool. Among the most influential soil microbiota are the mycorrhizal fungi, which establish symbiosis with plant roots. The mycorrhizal fungi help in the release of N and P from the detrital materials of microbial, faunal and plant origins (Read and Perez-Moreno 2003).

In agroforestry systems which integrate livestock, urine and dung deposition by animals which rest and feed under tree shade may also provide significant nutrient inputs. For example, in the parkland agroforestry in the Sahel, livestock feed on crop residues, tree leaves and pods, and deposit manure in the fields, thus helping nutrient recycling (Bayala et al. 2014). Boffa (1999) cites studies in Burkina Faso, where the average amount of cattle dung under *Faidherbia* crowns was 11–180% higher than in the open field. It must be noted that the residual effect of dung under the trees from distant past may persist even if livestock were excluded for many years.

8.4 Soil Fertility Improvement

The ability of perennials used in agroforestry to improve soil fertility has been well documented in many reviews and meta-analysis (Sanchez and Palm 1996; Buresh and Tian 1998; Nair et al. 1999). Specifically, the ability of leguminous species to replenish soil N and crop productivity on degraded lands has been demonstrated through meta-analyses (Sileshi et al. 2008b, 2014; Sileshi 2016). For example, N-fixing trees can support maize yields of up to 4 Mg ha^{-1} without addition of inorganic N fertilizer (Sileshi et al. 2008b). However, higher maize yields of above 7 Mg ha^{-1} would require N inputs of up to 200 kg N ha^{-1}. In such cases, organic inputs will be insufficient and must be supplemented with inorganic N. For long-term sustainability, organic inputs have advantages over inorganic sources because

50–80% of applied N inputs through organic N is not used by the crop, and this N is incorporated into the various pools of SOM. Inorganic N sources do not have this property, and N from inorganic pools is also subjected to higher levels of leaching and denitrification compared to organic sources. Since the ability of perennials in N fertility has already been covered in Sect. 8.3.2.1, here we will only focus on soil P limitation and acidity.

8.4.1 The Problem of Phosphorus

Phosphorus (P), often identified as a key constraint to crop production, is abundant in most soils, but less than 10% of the total P supply is available at any time. In many tropical regions, soil P fertility is declining due to greater export of P through removal of harvested products and erosion than input of P (Sanchez et al. 1997). For example, in small-scale farming systems in Africa, crop harvest removes almost all the P accumulated by cereal crops (Sanchez et al. 1997). This can also be a serious problem in agroforestry practices such as improved fallows, intercropping and alley cropping where cereals are the main annual component. Unlike N, no process comparable to N fixation exists for biological inputs of P in agroforestry, and most studies have found little or no benefit of trees on inorganic soil P tests (Sanchez et al. 1997).

Tree biomass, when added in realistic amounts, provides less P than that required to obtain adequate crop yields. This inadequacy is due to low P concentration of plant residues which is generally less than 3 g P kg^{-1} (Table 8.3). Application of high-quality residues (with 3 g P kg^{-1}) at 5 Mg ha^{-1} adds 15 kg P ha^{-1} compared to 18 kg P ha^{-1} required to grow 2 Mg ha^{-1} maize crop (Palm et al. 1997). This case shows that even application of large quantities of plant materials with high P concentrations cannot meet crop P demand. Therefore, mineral P fertilizers are required to obtain adequate crop yields on P limited soils.

Even though plant materials do not provide enough P, they do influence soil P levels and availability to crops. The possible mechanisms for improved P availability include (a) the mineralization of organically bound P in the organic inputs; (b) the

Table 8.3 Mean P concentrates, amount of P added in agroforestry prunings

Species	P concentration (g kg^{-1})	P added in 5 Mg ha^{-1} of prunings (kg P ha^{-1})
Calliandra calothyrsus	1.5 (0.4–2.3)	7.5
Gliricidia sepium	1.9 (1.2–2.8)	7.5
Leucaena leucocephala	2.0 (1.2–3.3)	10.0
Senna spectabilis	2.1 (1.4–2.7)	10.5
Sesbania sesban	2.3 (1.1–4.3)	11.5
Tithonia diversifolia	3.7 (2.4–5.6)	14.5

Source: Palm et al. (1999). Figures in parenthesis represent the range transformation of less available pools of inorganic P into more readily available organic P that is mineralized, when plants convert inorganic P in their tissues and those are cycled back to the soil; and (c) organic C radicals that can block P sorption sites (Sanchez et al. 1997). Perennial may be able to tap more unavailable forms of soil P as compared to annual crops through deep capture. However, if soils are inherently low in P and lack apatite in their parent materials no amount of recycling can recover P. Application of tree biomass to the soil has been shown to increase crop available P especially in the highly weathered tropical soils (Nair et al. 1999). For example, in *Gliricidia*-maize intercropping in southern Malawi, the addition of prunings and inorganic P application significantly reduced P sorption capacity of the soil (Mweta et al. 2007).

In addition, SOM contributes indirectly to raising P in soil solution by complexing certain ions such as Al and Fe that would otherwise constrain P availability. Decomposing organic matter also releases anions that can compete with P for fixation sites, thus reducing P adsorption. However, soil P contents and availability following addition of agroforestry prunings and litter depend on the amount of material added, the concentration of readily degradable carbon and the N/P and C/P ratios of the material (Palm et al. 1999; Stevenson and Cole 1999; Güsewell and Gessner 2009). Litter decomposition is P limited at N/P ratios >26 (Güsewell and Gessner 2009). Net P immobilization occurs during decomposition of residues when C/P is greater than 400 (Stevenson and Cole 1999).

Many tree species used in agroforestry systems are highly dependent on arbuscular mycorrhizal fungi (AMF) (Habte and Manjunath 1987; Hailemariam et al. 2018), which play a critical role in the uptake of relatively immobile forms of nutrients such as ammonium, P, calcium (Ca) and zinc (Zn) (Habte 2006). In a study conducted in Hawaii inoculation with AM fungi significantly increased P uptake by *Leucaena*. The concentration of P required by uninoculated *Leucaena* for maximum yield was 27–38 times higher than that required by mycorrhizal *Leucaena* (Habte and Manjunath 1987). Similarly, on a degraded Luvisol in southwestern Nigeria, inoculation with AM fungi increased N, P, Mg and K uptake in *Gliricidia*. Inoculated plants also extracted more water from the 0–30 cm depth than the uninoculated ones (Okon et al. 1996). The enhanced P uptake is often accompanied by significant increases in tree growth and biomass production.

Studies have shown that the volume of soil explored by mycorrhizal roots can exceed that explored by uninfected roots by a factor of more than 100 (Habte 2006). In addition, AM can induce changes in root morphology such as root branching and root elongation, thus increasing the volume of soil from which plant roots can explore nutrients. AM fungi may also have biochemical and physiological capabilities for increasing the supply of available P or other immobile nutrients in the soil system. These mechanisms include acidification of the rhizosphere, excretion of chelating agents and increases in the activity of phosphatase enzymes that can mobilize phosphate tied up in SOM (Habte 2006). Some ECM and other mycorrhizal fungi also exude large amounts of lytic enzymes and organic acids, which in turn release recalcitrant organic and mineral P into the soil. These processes can bypass organic P mineralization by free-living decomposers, effectively short-circuiting soil-plant P cycling (Jansa et al. 2011).

8.4.2 Managing Soil Acidity

Soil acidity is among the major land degradation problems worldwide, affecting about 30% of the ice-free soils (about 4 billion ha) and 32% of all arable land (Eswaran et al. 1997). Acidic soils are characterized by deficiencies of P, Mo, Ca and Mg in the soil and toxicities of aluminium (Al), magnesium (Mg), iron (Fe) and H ions. Soil acidity also affects activities of beneficial microorganisms, BNF, decomposition of organic matter, nutrient mineralization and immobilization, uptake and utilization by plants and consequently crop yields. As such soil acidity is a major cause of soil infertility. Liming has been the traditional solution to acid soils. However, in most developing countries lime is not readily available due to the large quantities needed.

The first step in managing acidic soils is to initiate the process of deep capture and pumping nutrients to produce enough biomass that initiates soil improvement (Husson et al. 2006). Planting trees could minimize soil acidification both by decreasing drainage and by recycling leached nutrients. Leguminous materials are also useful in managing soil acidity because they have high ash alkalinity and thus provide cash-limited farmers with a biological means of liming acid soils (Mafongoya et al. 2006). However, the acid ameliorating effect of plant materials depends on their chemical composition (Moody and Aitken 1997; Wong et al. 2002). Under some conditions, the soil fertility benefits of planting legume trees could be offset by soil acidification. For example, *Leucaena*-based pasture produced 1 k mol H^+ ha^{-1} $year^{-1}$ and acidified the soil down to 40 cm in Queensland (Noble et al. 1998).

In general, the acidity generated by N fixation varies between 0.2 and 0.7 mol H^+ per mol of fixed N (Bohan et al. 1991). This universal requirement for maintaining electrical neutrality also results in proton release during the uptake of ammonium, and approximately 1 mol H^+ is released per mol of ammonium taken up and assimilated. Similarly, the uptake of nitrate and its assimilation in roots would release about 1 mol OH per mol of nitrate (Moody and Aitken 1997). Tropical legumes typically take up less cation and have lower acidifying effect on the rhizosphere because the amino acids produced by N fixation have lower propensity to release protons (Bohan et al. 1991). It is removal of this plant biomass together with its ash alkalinity that results in soil acidification at the site of N fixation. Legume grains have lower ash alkalinity than shoots and removal of grain only from the harvested area will minimize acidification. Removal of 1 Mg of grain generates acidity requiring 15–35 kg $CaCO_3$ to neutralize, whereas removal of 1 Mg of shoots requires 55–100 kg $CaCO_3$ (McLay et al. 1997). Removal of cut pasture materials has a similar effect, which is diminished by grazing due to the return of alkalinity in the form of animal manure (Wong et al. 2002). If the bulk of the leguminous plant biomass decomposes on site, then the ash alkalinity is released, and soil acidification is minimized (Wong et al. 2002). An example is improved fallows in eastern Zambia, where pruning materials are incorporated in the soil on site. Measurements of soil pH in October 1997 and October 2000 revealed no acidification in the soil profile to a depth of 2 m. The tendency was for the soil pH to increase slightly over that period. This is probably because the perennials in these agroforestry systems minimized soil acidification both by decreasing drainage and by recycling leached nutrients (Mafongoya et al. 2006).

Management of soil acidification under agroforestry should therefore aim at selecting appropriate low acidifying genotypes, at minimizing the removal of biomass from the site of production and at minimizing nitrate leaching. Localized acidification may be beneficial in circumstances where alkalinity accumulates down in the soil profile. In these circumstances, the use of acidifying legumes allows the alkalinity to be accessed and made available in the form of biomass with high ash alkalinity. The acid ameliorating effect of this biomass can then be used in more acid parts of the landscape or in the more acid topsoil. Agroforestry has a large potential for optimizing nutrient cycling and managing soil acidity in this manner (Wong et al. 2002).

8.5 Challenges to Maximizing Nutrient Cycling in Agroforestry

While agroforestry can ensure greater nutrient cycling and restore degraded land, there are many challenges to establishing trees successfully on such land. One of the key challenges is the low survival rate of trees and finding suitable species for specific condition. While N-fixing tree species can grow on soils where low levels of available N prevent natural vegetation successions (Sileshi et al. 2014), their survival, growth and N fixation could be limited by low P and moisture stress in degraded drylands. For example, applying P and inoculating Faidherbia seedlings with indigenous AMF is necessary to improve its growth in drylands in Ethiopia (Hailemariam et al. 2018). Similarly, in low-P soils *Leucaena* barely forms nodules unless the P status of the soils is first improved or the soil is inoculated with AMF (Habte 2006).

In the humid tropics, soil acidity may constrain establishment of some tree species used in agroforestry interventions. Soil acidity has long been known to decrease symbiotic N fixation, negatively affecting growth and yield in legumes (Ferreira et al. 2016). Strongly acidic soils ($pH < 5.5$) suffer from low levels of P and Ca, and they may contain toxic levels of Al and manganese (Mn) (Husson et al. 2006). Many leguminous tree species grow poorly or cannot grow at all on these soils. Therefore, it is important to inoculate such trees with effective N-fixing bacteria and AMF to improve their establishment on acid soils. AMF can help to overcome P deficiencies and stimulate nodulation and N fixation through their effect on improved P, Cu, Zn, Ca and Fe availability to the legume trees (Habte 2006). However, access to the right strains of N-fixing bacteria and AMF is limited in many areas. On degraded land where tree establishment is problematic, it is worthwhile to try bamboos. Because of their fast growth (and therefore short rotation cycle), and high regeneration rate after harvesting, bamboos can rehabilitate degraded land more quickly than trees (Tewari et al. 2015).

In the past, many agroforestry projects have depended on promoting exotic species for ameliorating degraded lands. However, farmer adoption of exotic species has been generally slow. Empirical evidence suggests that establishment of agroforestry may be best achieved by allowing natural regeneration of trees, avoiding mechanized tillage and exclusion of animals and human activity in degraded lands. For example, farmer-managed natural regeneration (FMNR) or the assisted natural regeneration of trees has been successful in the Sahel region of West Africa (Shono et al. 2007; Haglund et al. 2011; Reij and Garrity 2016). Exclosures have also been promoted through active participation of communities and local authorities in Ethiopia to rehabilitate degraded communal grazing lands (Mengistu et al. 2005). Exclosures are areas from which animals and humans are excluded with the goal of promoting natural regeneration of plants and rehabilitating degraded lands. FMNR is a simpler, inexpensive and more effective alternative to reforestation for converting areas of degraded land to more productive land (Shono et al. 2007). Reij and Garrity (2016) present examples of large-scale FMNR in West Africa. They also proposed a scaling-up strategy to create new agroforestry systems based on the experience from the Sahel.

8.6 Conclusions and Implications for Management

The studies reviewed suggest that agroforestry systems can ensure greater internal nutrient recycling on degraded lands. Soil improvement could be achieved through nutrient cycling via deep capture and increased supply via biological N fixation, addition of tree biomass and litter in to the soil and recycling of nutrients through litter decomposition mediated by soil biota. Deep capture of nutrients by tree roots can also recycle nutrients leached when inorganic fertilizer is applied by farmers, thus improving nutrient use efficiency and reducing negative environmental consequences. The literature surveyed provided ample evidence that use of organic matter from perennials can play a critical role in ameliorating soil acidity through deep capture of nutrients and biomass production.

The review also highlights that substantial areas of degraded land can be reclaimed using agroforestry practices. Large-scale adoption of agroforestry practices with promotion of locally adapted species can improve land productivity or reverse degradation. Phosphorus is often the critical nutrient in improved fallows, intercropping and alley cropping, where P is removed with crop harvest. Therefore, inorganic sources of P must be applied to these systems to replenish the soil P and improve productivity of N-fixing trees. Initial tree establishment on degraded land may be challenging due to soil P deficiencies and water stress. Therefore, we strongly recommend the routine application of P fertilizer and inoculation of tree seedlings with appropriate N-fixing bacteria and mycorrhizal fungi to ensure better tree establishment in drylands.

Most of the agroforestry systems in the literature reviewed were trees and shrubs; bamboos seem to have remained underutilized. Given their fast growth and soil binding properties, bamboos are ideal for use in rehabilitation of degraded lands. Therefore, we recommend their increased use in agroforestry initiatives.

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9 Potential of *Gliricidia*-Based Agroforestry Systems for Resource-Limited Agroecosystems

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Abstract

Over the last decades, considerable attention has been paid to the identification and introduction of suitable tree species in agroecosystems to simultaneously address soil degradation, food insecurity and climate change impacts. *Gliricidia* (*Gliricidia sepium*) has many desirable characteristics as an agroforestry tree species, and its performance has been widely studied in humid and subhumid regions, but to a lesser extent in drylands and agroecosystems with severe moisture and nutrient limitations. Much of the earlier work has also focused on assessments using selected metrics of agronomic performance. In this chapter, we applied indicator-based assessments with the objectives of (1) providing an up-to-date synthesis of the potential of *Gliricidia*-based agroforestry practices to sustainably intensify resource-limited agroecosystems and (2) creating awareness

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among researchers, development agencies and policymakers on the long-term benefits of such practices. The various *Gliricidia*-based agroforestry practices performed well when judged against the key indicators of sustainable intensification under productivity, economic and environmental sustainability and human well-being. It is concluded that *Gliricidia*-based practices also meet the central requirements for agroforestry trees in resource-limited agroecosystems, i.e. that the trees (1) can acquire resources that associated crops would not otherwise get, (2) have positive effects on crops, (3) ensure more closed nutrient cycling and (4) enrich the soil with organic matter and nutrients.

Keywords

Biomass transfer · Fallows · Indicators · Intercropping · Sustainable intensification

9.1 Introduction

Resource limitation is a universal phenomenon in many ecosystems, and it is generally associated with reductions in rates of resource uptake, biomass production or growth caused by low availability of energy and materials, such as carbon, nutrients and water (Craine 2013). In agroecosystems, nutrient limitations are often consequences of soil degradation processes, including accelerated erosion, depletion of the soil organic carbon (SOC) pool, loss of biodiversity and soil fertility, elemental imbalances, acidification and salinization (Lal 2015). These processes affect large areas of agricultural land globally, with varying degrees. For example, in sub-Saharan Africa (SSA), about 494 million ha of the land is affected by one form of degradation or another. Of this, 46% is by water erosion, 38% by wind erosion, 12% by chemical degradation and 4% by physical degradation (FAO and ITPS 2015). Similarly, in India, an estimated 90 M ha of the agricultural soils is affected by water erosion, 16 M ha by acidification, 14 M ha by flooding, 9 M ha by wind erosion and another 6 M ha by salinity (Nath et al. 2018). In Central Asia, which is one of the largest irrigated areas in the world, extensive degradation of irrigated croplands occurs due to increasing soil salinity and depletion of soil nutrient stocks (Khamzina et al. 2009). In large areas of Southeast Asia, soils have become so degraded that they are abandoned and have become invaded by *Imperata* grass (Garrity 1997).

Soil degradation results in soil quality decline (Lal 2009) with attendant reduction in ecosystem functions and services (Lal 2015). Therefore, minimizing soil degradation is essential to manage resource limitations and maintain the ecosystem services provided by soils (FAO and ITPS 2015). Soil degradation can be reversed by adopting practices that minimize soil erosion, create positive SOC and nitrogen (N) budgets, enhance activity and species diversity of soil biota and improve structural stability (Lal 2015).

In many agroecosystems, N followed by phosphorus (P) and to a lesser degree potassium (K) and sulphur (S) are the most limiting nutrients (Kihara et al. 2017; LeBauer and Treseder 2008; Liu et al. 2010). Recent global analyses (LeBauer and

Treseder 2008; Liu et al. 2010) show that N limitation is widespread but particularly severe in Africa and Asia. The N inputs in agroecosystems are possible through fertilizer inputs, biological N fixation (BNF) and the retrieval and subsequent cycling of N from below the reach of crop roots (Buresh and Tian 1998). N-fixing trees have the potential to be self-sufficient in N when planted in degraded lands, including saline soils (Djumaeva et al. 2010). Competition for water and nutrients between trees and crops may be a problem in water- or nutrient-limited environments unless the trees have deep roots to exploit water and nutrients below the crop rooting zone. Deep rooting trees are expected to redistribute soil water and nutrients in the upper soil layers, resulting in more efficient use by crops (Ewel and Mazzarino 2008).

Over the last decades, considerable attention has been given to the identification and introduction of deep rooting and N-fixing woody species in agroforestry systems (Sanchez et al. 1997). Management of such trees in agroforestry is believed to simultaneously contribute to increased food production (Akinnifesi et al. 2010), climate change mitigation and adaptation in agriculture (Verchot et al. 2007) and conservation of soil biodiversity (Barrios et al. 2012). Among agricultural mitigation options, soil C sequestration is one of the few strategies that could be applied at large scales to benefit smallholder farmers (Nath et al. 2018). Nevertheless, the adoption of agroforestry has been slow in some countries due to lack of information, planting materials and extension and policy support. It is common for agroforestry practices to incur a loss in the first year and take several years before benefits accrue, and this can discourage farmers from adopting. However, over the long-term, benefits from agroforestry generally outweigh those from crop monocultures, and the system is often more sustainable (Ajayi et al. 2011).

Among the central requirements for the ideal agroforestry tree are the following: (1) ability to acquire water and nutrients that the associated crops would not otherwise get, (2) have net positive effects on yields of associated crops, (3) building SOC and nutrient stocks through litter inputs and root turnover, (4) increasing soil nutrient availability by ensuring a more closed nutrient cycling and (5) reducing soil erosion rates by improving soil physical and biological properties (Barrios et al. 2012; Cannell et al. 1996; Sanchez et al. 1997).

Gliricidia (*Gliricidia sepium* Walp), a species native to Central America, is now widely grown in North America, Africa, Asia and Australia (Wise and Cacho 2005). *Gliricidia* has been used extensively outside its native range. After *Leucaena* (*Leucaena leucocephala* (Lam.) de Wit.), *Gliricidia* is the most widely cultivated multipurpose tree. In most situations, *Gliricidia* yields more biomass than *Leucaena* and has fewer pests and diseases, besides its ability to grow in a wide range of soil types and altitudes (Hughes 1987; Stewart et al. 1996). *Gliricidia* is adapted to infertile acidic soils (pH range: 4.5–6.2). It can also grow at altitudes ranging from sea level up to 1100 m and annual rainfall of 650–3500 mm (Stewart et al. 1996). *Gliricidia* tolerates repeated cutting and resprouts vigorously after cutting. Its high biomass production and quality of the leaf makes it an important forage crop.

Gliricidia has many desirable characteristics as an agroforestry tree species (Stewart et al. 1996). The tree can grow to about 8 m high in the absence of cutting. If cut, pruned or lopped, it readily coppices (produces new shoots), making it easy to fit in any cropping system. *Gliricidia* has a long history of use in traditional agroforestry practices, where shade-loving crops, such as cacao and coffee, are grown. For example, the Aztec and Spanish names of *Gliricidia*, "cacahuanantl" and "madre de cacao", literally mean "mother of cacao", indicating that *Gliricidia* was associated with cacao (*Theobroma cacao*) agroforestry for millennia in the Americas (Kass et al. 1997). Similarly, in cacao plantations in Central Sulawesi, *Gliricidia* is the most commonly planted shade tree (Schwendenmann et al. 2010). In the drier and more water- and nutrient-limited tropical and subtropical regions, *Gliricidia*-based agroforestry practices are increasingly used for sustainable intensification of annual crop and livestock production systems (Sileshi et al. 2014). The fresh leaves and branches can be incorporated into the soil to increase soil fertility, where cereals or vegetables are grown (Akinnifesi et al. 2010; Kuntashula et al. 2006; Sileshi et al. 2011). It is also a good fodder tree; its leaves are fed to livestock (Chakeredza et al. 2007).

Gliricidia-based agroforestry practices have been widely studied, especially in the humid and subhumid tropical and subtropical regions, but there is a dearth of information on the performance of these practices in drylands and agroecosystems with severe moisture and nutrient limitations. In addition, much of the earlier work has focussed on assessing the performance of these practices using selected metrics (i.e. specific properties of a system that can be directly measured) of agronomic performance. In this synthesis, we apply indicator-based assessment of the potential of these practices in sustainability intensifying resource-limited agroecosystems. Indicators are frequently used at the science-policy interface (Heink and Kowarik 2010) to assess or model complex world processes to aid decision-making. Compared to simple metrics, indicators serve as more powerful tools in evaluating the impacts of specific interventions and making political decisions for achieving sustainability. Therefore, the objectives of this chapter were the following: (1) to provide an up-to-date synthesis of the potential of *Gliricidia*-based agroforestry to sustainably intensify resource-limited agroecosystems and (2) to create awareness of the long-term benefits of these practices among researchers, development agencies and policymakers. Here we also assess whether *Gliricidia* satisfies the requirements for the ideal agroforestry species or not.

9.2 Methods

9.2.1 Literature Review

A review of the literature was undertaken to identify *Gliricidia*-based agroforestry practices and the influence of the tree on soil, crop and animals. The review also involved identification of suitable indicators and indices of sustainable intensification against which the potential of *Gliricidia*-based agroforestry systems can be judged. Relevant information was assembled from both published and unpublished literature through a comprehensive literature search. The review put more weight to long-term studies (>3 years) because it takes several years for benefits to accrue in tree-based land use systems. *Gliricidia* takes 2–3 years to become fully established and to produce enough biomass to bring about observable changes in crop yields and soil properties.

9.2.2 Identification of Indicators

In this analysis, we used indicators of sustainable intensification derived from routinely collected agronomic, soil and water data in *Gliricidia*-based agroforestry systems. Sustainable intensification (SI hereafter) is defined as producing more output from the same area of land while reducing the negative environmental impacts and, at the same time, increasing contributions to natural capital and the flow of environmental services (Pretty et al. 2011). Several indicators of SI are available in the literature, and these fall under five major domains, namely, productivity, environmental sustainability, economic sustainability, social sustainability and human well-being (Smith et al. 2017).

The main indicators of productivity in crop and livestock production systems include crop yield, biomass production, crop diversity, fodder production, input efficiency, water use efficiency and yield variability (Smith et al. 2017). Yield is indexed by the production of crops per unit of land area (Mg grain ha^{-1}) in crop production systems, while in livestock systems, yield is measured as the production of animal products (milk, meat or eggs) per animal per day, or the production of milk per animal per lactation period (Smith et al. 2017). Yield variability, usually indexed by the coefficient of variation (CV), is another important but less frequently used indicator (Smith et al. 2017). Yield stability is also becoming an important metric. For the present analysis, we chose crop yield, yield variability and fodder yield.

The most frequently cited indicators of environmental sustainability are soil quality, biodiversity, carbon sequestration, greenhouse gas (GHG) emission and erosion control. Soil quality generally refers to the capacity of the soil to support and sustain agricultural production, and it is used as the main indicator of soil health (Barrios et al. 2012). Soil quality is often divided into physical, chemical and biological. The common metrics of soil physical quality include soil hardness, aggregate stability, available water capacity, infiltration rate and effective rooting depth (Lal 2015). Relevant metrics of soil chemical quality include pH, CEC, nutrient availability, carbon to nitrogen ratio (C/N), C and N mineralization rates, electrical conductivity, salinity, sodicity and toxicity (Lal 2015). The commonly used metrics of soil biological quality are soil organic matter (SOM) or SOC, and the abundance and diversity of soil fauna and flora are often used as suitable indicators (Lal 2015). We selected SOM (or SOC), soil nutrient availability and uptake, carbon sequestration, GHG emission, erosion control and diversity of fauna for this review as they were more frequently mentioned, and data were available in the long-term trials reviewed.

To judge economic sustainability, several indicators have been suggested, but agricultural income, labour productivity and input access are the most frequently used indicators in the SI literature (Smith et al. 2017). In this review, we used labour productivity, benefit cost ratios and net present value as indices of economic sustainability of *Gliricidia*-based agroforestry practices.

Among the indicators of human well-being, the most important ones are food safety, food and nutrition security, labour saving and risk reduction (Smith et al. 2017). Risk is generally measured as either production risk or perceived risk. Production risk can be quantified as the probability that crops will produce sufficient yield to meet the food or nutritional needs of the household. In this analysis, we mainly used food and nutrition security and production risk due to availability of data.

9.2.3 Case Studies

In this section, case studies were chosen to highlight specific success stories. Here, the potential of *Gliricidia*-maize intercropping to mitigate the effects of extreme events on maize productivity was assessed using data from four long-term experiments. This case study was chosen with the background that climate change is anticipated to harm maize production with up to 95% chance in the absence of adaptation measures in SSA (Lobell et al. 2011).

The first three experiments involved *Gliricidia*-maize intercropping on two subhumid sites with a monomodal rainfall pattern (November–March). The first experiment was established on Lixisols in 1991 at Makoka Agricultural Research Station in Southern Malawi and run for 14 consecutive years. The study site and management of the experiment have been described in detail in Akinnifesi et al. (2006). The second and third experiments were established on Luvisols at Msekera Research Station in Eastern Zambia in 1991 (Experiment 91–3) and 1992 (Experiment 92–3). By the time of analysis, these experiments were run for 11 and 12 consecutive years. The management of these experiments has been described in detail elsewhere (Sileshi and Mafongoya 2006). At both the Msekera and Makoka sites, *Gliricidia* seedlings were planted in pure stands and manged as fallows. At the end of the fallow period (36 months), trees were cut at 0.3 m height, and the leaf and twig biomass was incorporated into the soil. Since then, the resprouts were pruned 3–4 times every year, and pruning biomass was incorporated into the soil. Continuous monoculture maize crops were grown with and without fertilizer input for 11–14 consecutive years.

The fourth study involved alley cropping established on a Luvisol at Ibadan in Nigeria, a subhumid site with a bimodal rainfall pattern with two growing seasons: the main season (April–July) and minor season (September–October). The experiment was run for 12 years (1981–1993). The experiment involved hedgerow intercropping of *Gliricidia*, maize grown without N fertilizer as well as half and full rate of the recommended N fertilizer during the main cropping season. Each hedgerow intercrop had two subplots: one where maize was grown with the full rate of fertilizer and the other subplot with half of the recommended rate. Details of the experimental design and management are given in Kang et al. (1990). For all the study sites, we calculated rain use efficiency (RUE) as a proxy for water use efficiency. We used the coefficient of variation (CV) to determine the inter-annual yield variability in RUE and yield stability.

9.3 Typology and State of Knowledge of *Gliricidia*-Based Agroforestry Practices

9.3.1 Multistrata Agroforestry

Multistrata agroforestry is defined as a land use system with two or more vegetation layers and more than one tree species (Schroth et al. 2001). Multistrata agroforestry practices range from the simplest form consisting of plantations of coffee (*Coffea* spp.), cacao (*Theobroma cacao*) or tea (*Camellia sinensis*) grown with shade trees to complex and highly diversified systems with a forest-like structure, such as homegardens and agroforests (Schroth and do Socorro Souza da Mota 2014). These complex mixtures of trees and agricultural crops are widely practiced in Latin America, Southeast Asia and Equatorial Africa (Kass et al. 1997). N-fixing trees are an important component of the simple multistrata systems where globally important cash crops are produced.

Shaded plantations of cacao and coffee are probably the most important *Gliricidia*-based agroforestry systems. Due to the shade requirement of young cacao plants, cacao is cultivated under shade trees to reduce the stress due to high evaporative demand and radiation intensity (Abou Rajab et al. 2016). The trees also provide other functions, including erosion control and nutrient cycling (Beer et al. 1998). As a shade tree, *Gliricidia* is managed by regular pruning or lopping for shade adjustment (Stewart et al. 1996).

Nitrogen fixation by *Gliricidia* (estimated at >100 kg ha^{-1} yr^{-1}) can contribute to increased N availability to the cocoa plants through litter fall, pruned biomass and roots decay and exudation. Shade trees may also provide substantial inputs of litter fall to the system. For example, in Indonesia, annual litter production of *Gliricidia* trees amounted to 3.9 Mg ha^{-1} (Moser et al. 2010). The litter inputs build the soil organic matter (SOM), increase the cation-exchange capacity of the soil and favourable carbon-nitrogen ratio for cocoa production (Beer 1988). Increased litter from shade trees may also promote the diversity of decomposer organisms and other species that can provide ecosystem services, such as pest control (Tscharntke et al. 2011).

9.3.2 Alley Cropping Hedgerow Intercropping

Alley cropping (also called hedgerow intercropping) is an agroforestry practice, where trees or shrubs are grown in wide rows and arable crops (cereals, legumes or horticultural) or pasture grasses are cultivated in the alleys between the tree rows. In the tropics, alley cropping was developed as an alternative to slash-and-burn agriculture and for erosion control on sloping land (Kang et al. 1990). Alley cropping is widely practiced in the Americas (Oelbermann et al. 2004; Zinkhan and Mercer 1996), Europe (Medinski and Freese 2012), Asia and Africa (Kang et al. 1990). In the temperate regions, alley cropping of high-value (e.g. timber, fruit or nut-bearing) trees with crop or pasture is the more common practices. In the humid and subhumid tropics of Africa, alley cropping is practiced in the cereal-root crop mixed and maize-mixed farming systems, where it involves growing maize, beans or cassava between rows of *Gliricidia* and other legume trees (Kang et al. 1990). At Machakos in Kenya, above- and below-ground interactions have been studied for over a decade in alley cropping with *Gliricidia*, where maize was planted annually in 8 m wide alleys (Odhiambo et al. 2001). However, pruning *Gliricidia* is important in this system, especially in the drylands to reduce below-ground competition. Pruning often reduces tree root densities. For example, on a semi-arid site in Northern Kenya, pruning decreased the total root length density of *Gliricidia* trees by 47% over unpruned trees (Lehmann et al. 1998). The presence of woody species in the alley cropping production system has been shown to contribute to (1) nutrient recycling, (2) reduction in soil nutrient leaching losses, (3) stimulation of higher soil faunal activities, (4) soil erosion control, (5) soil fertility improvement and (6) sustained levels of crop production. These experiences can be utilized in developing sustainable and environmentally friendly agroforestry systems (Kang 1997).

9.3.3 Improved Fallows and Rotational Woodlots

Improved fallows involve the deliberate planting of fast-growing woody species for the rapid replenishment of soil fertility (Sanchez et al. 1997). Improved fallows are usually promoted as an alternative to natural vegetation fallows for improving soil fertility and reclamation of degraded crop land. A piece of land is planted with fast-growing nitrogen-fixing trees such as *Gliricidia* or shrubs for 2–3 years (Mafongoya et al. 2006). When the trees are cut, the leaf and litter biomass from *Gliricidia* is incorporated into the soil, and this can increase the organic matter, soil N, P, and potassium (K) contents. In addition, the organic matter can raise and stabilize the soil pH level.

9.3.4 *Gliricidia*-Maize Intercropping

Gliricidia-maize intercropping was adapted from alley cropping technologies to meet the needs of smallholder farmers with limited access to credit or land.

Intercropping involves planting cereals, such as maize and sorghum, between rows of coppiced trees. *Gliricidia*-maize intercropping has been widely applied in densely populated areas, such as Malawi and Western Kenya, where sizes of land holdings preclude fallows (Akinnifesi et al. 2007; Jama et al. 2006). Intercropping has been designed for farmers with small landholding sizes that cannot allow for traditional fallow practices.

Gliricidia-maize intercropping is an improvement building on lessons from alley cropping and aimed at minimizing limitations, such as the "hedge effect", and competition between tree and crops. A typical example is the *Gliricidia*-maize intercropping in Malawi and Zambia (Akinnifesi et al. 2010). In this practice, every row of maize is grown adjacent to a row of coppiced *Gliricidia*, where the pruned biomass is incorporated into the soil in the row of maize 3–4 times a year. Tree spacings do not maintain hedges but are rather interspaced at 1 m within-row by 2 m between-row. At cutback, trees are pruned at 30 cm above-ground level. Details of tree management in *Gliricidia*-maize intercropping in Malawi and Zambia has been described in detail elsewhere (Akinnifesi et al. 2006; Sileshi and Mafongoya 2006). Research conducted in Malawi and Zambia show that *Gliricidia* trees can coppice and produce biomass for more than 15 years. This greatly reduces labour and seed requirements to the smallholder farmer without significant decrease in biomass production (Akinnifesi et al. 2010; Sileshi et al. 2012). At Msekera in Eastern Zambia, over a period of 9 years, annual coppice biomass ranged between 0.3 and 3.7 Mg ha^{-1} (mean: 2.1 Mg ha^{-1}).

Tree and crop roots in simultaneous agroforestry systems often compete when their nutrient depletion zones around the roots overlap in the soil mass. Such interactions in intercropping systems between component species occur as a response of one species to the environment as modified by the presence of the other species (Akinnifesi et al. 1999a, b, 2004). Because species in intercropping system must share a limited pool of belowground resources, competition can be triggered, with the more aggressive species benefitting while the weaker species becomes the loser. These interactions may be competitive (adverse), complementary (beneficial) and/or neutral (balance-off).

Root architecture, the distribution of plant roots vertically and laterally, in multispecies agroecosystems generally depends, among other factors, on ecological zone, plant genotype, tree management, cropping systems and soil physico-chemical characteristics and precipitation. For instance, rooting patterns and distribution of eight agroforestry tree species varied under alley cropping system in Ibadan, Nigeria (Akinnifesi et al. 1999b). High below-ground competition takes place between agroforestry trees and the associated crop, when most of the tree roots are confined to the same soil strata as the associated annual crop.

An important feature of the *Gliricidia*-maize intercropping is the spatial separation of the root systems (Fig. 9.1), leading to complementary resource use by the tree and maize crops (Makumba et al. 2009). Schroth (1999) identified the need to distinguish between rooting depth and root distribution in the entire soil profile. Shallow-rooted plants that exhibit a rapid decline in root mass, length or density with increasing soil depth may be more competitive than those which have a lot of fine

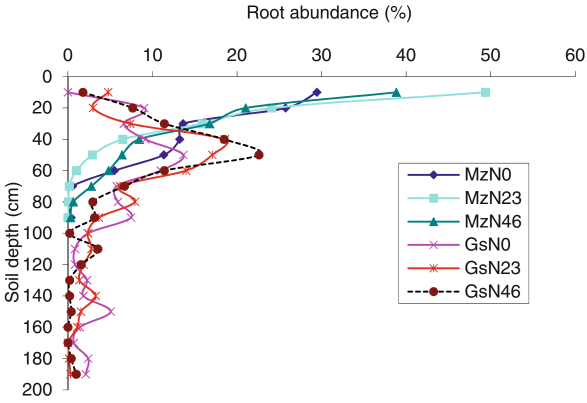

Fig. 9.1 Effect of N application on root abundance of *Gliricidia sepium* and maize in a simultaneous fallow intercropping system in Makoka, Malawi [MzN0 = sole maize without nitrogen input (control), MzN23 = sole maize receiving 23 kg N ha^{-1}, MzN46 = sole maize receiving 46 kg N ha^{-1}, GsN0 = *Gliricidia*-maize intercropping without N fertilizer; GsN23 = *Gliricidia-maize* intercropping receiving 23 kg N ha^{-1}; and GsN46 = *Gliricidia*-maize intercropping receiving 46 kg N ha^{-1}]

roots in the topsoil and yet maintain a substantial proportion of roots in the deeper soil layers. Tree species with lateral roots, confined to less than 1 m distance from the tree trunk, are more desirable in simultaneous agroforestry systems that require tillage of the inter-row spaces. *Gliricidia* meets this condition in intercropping system in Malawi. The study by Makumba et al. (2009) concluded that *Gliricidia* is an ideal tree species for the intercropping system in Malawi because of its low surface rooting as well as its deeper and stratified roots in the study site.

Gliricidia has been able to survive prolonged and seasonal droughts in intercropping systems (Akinnifesi et al. 2010; Sileshi et al. 2012). This can be explained by tree roots abundance at soil depths that are below the feeding zone of most annual crops that may transfer deeper resources to the surface, enabling better survival of trees during long periods of drought or water stress (Akinnifesi et al. 2004). However, the rooting pattern of *Gliricidia* in humid tropical environment is different from subhumid and semi-arid conditions. Trees in high rainfall zones may develop more vigorous lateral roots than in the semi-arid conditions. Trees adapted to semi-arid conditions are well known for having deep root systems and less superficial rooting.

Studies demonstrate that generalized assumptions about root distribution and depth may not hold for *Gliricidia* when it is planted in different soil types and rainfall conditions. For instance, *Gliricidia* roots when grown in a Ferric Lixisol (pH 5.4) in Makoka, Malawi, were few at the surface layer (rooting zone of crops), with more concentration at a depth of 30–60 cm below the crop rooting zone (Fig. 9.1), thereby showing non-competition (Makumba et al. 2009). Instead, this vertical displacement became an advantage as tree roots were able to intercept nutrients and water that would have otherwise been leached below rooting zone of associated maize crops (Makumba et al. 2009). Whereas, in an Ultisol (pH 4.8) in Lampung, Indonesia, the roots of *Gliricidia* were reported to be highly concentrated in the topsoil. On a low altitude and high rainfall site, *Gliricidia* had 85% of its roots in the top 0–30 cm soil layer, while it had less than 33% of its roots at the same depth in a drier environment in Southern Malawi. Likewise, in an Ultisol in Sumatra, Indonesia, Hairiah et al. (1992) showed that under *Gliricidia* had relatively few branch roots. Akinnifesi et al. (2004) concluded that *Gliricidia* is a suitable ideotype for simultaneous tree-crop intercropping systems. It has deeper and stratified roots in low rainfall and high-altitude environments.

Similarly, Schroth and Zech (1995) found that root length density of the hedgerows was too low to compete with the crops for soil resources in a semi-deciduous rainforest zone of West Africa. In addition, the hedgerows tended to increase root length densities in the subsoil when few roots were present, thus, possibly reducing the risk of nutrient leaching. In general, shallow-rooted trees are commonplace in strongly acidic soils; rooting depth is often dictated by mechanical soil impedance in drier soils.

Tree pruning management also has an important influence on rooting systems of trees. In an alley cropping experiment with *Leucaena* in Ibadan, Nigeria, Akinnifesi et al. (1995) demonstrated that rooting intensity and density of trees are reduced when subjected to frequent pruning compared with unpruned fallows. However, denser roots of unpruned trees are likely to be more efficient in nutrient cycling but exhibit higher root competition with crops above- and below-ground. Both roots of tree and maize were enhanced by the mineral N fertilizer application. Maize being an aggressive N user seemed to have forced *Gliricidia* roots downwards in intercropping systems when trees are pruned. In another excavation, at Makoka, Malawi, *Gliricidia* attained 5.6 m soil depth (Akinnifesi et al. 2004).

9.3.5 Contour Hedges

A contour hedge is a horizontal strip of multipurpose trees such as *Gliricidia* or shrubs that is used for soil erosion control on sloping lands (Jama et al. 2006). The hedges, at the same time, provide high-quality fodder, firewood, stakes for climbing beans and mulch material. Contour hedges control erosion by providing a physical barrier as well as through increased infiltration because of a leaf litter layer creating good soil structure. Over the long term, these hedges result in the formation of terraces on the upper side of each hedge.

9.3.6 Biomass Transfer

Biomass transfer involves moving green leaves and twigs from trees grown in one location to another field for application to other crops. Biomass harvested from *Gliricidia* trees and used as green manure has been demonstrated to improve soil fertility under smallholder farm conditions on nutrient-limited sites in Zambia

(Kuntashula et al. 2006), Malawi (Sileshi et al. 2011), and Kenya (Rao and Mathuva 2000). Recent studies (Kuntashula et al. 2004, 2006) have shown that biomass transfer using fertilizer-tree species is a more sustainable means for maintaining nutrient balances in maize- and vegetable-based production systems. The legume biomass can be applied alone or combined with small amounts of inorganic fertilizer. Although the *Gliricidia* biomass can be applied to any crops, the harvesting and transporting of biomass demands a lot of labour. Therefore, the use of *Gliricidia* biomass is used on high-value crops, such as vegetables.

Biomass that is applied to the crop can be obtained from either a biomass bank or a coppicing fallow. The biomass bank is a stand of trees, in this case *Gliricidia*, specially raised to provide leafy biomass. In the coppicing fallow systems using *Gliricidia,* the trees are cut 2–3 times during the maize-growing season. Hence, at maize harvest, the *Gliricidia* would have grown so much that there will be excess coppice biomass. This coppice biomass can be harvested in May or June in case of most SSA region and carried to the *dambos* to be applied to vegetable plots. The *Gliricidia* will have enough time to grow using residual moisture during the dry season (May–November) to have enough biomass to be cut and applied to maize at the beginning of the wet season (Akinnifesi et al. 2006). Through this system, farmers can grow three crops, namely: (1) maize in the upland, (2) vegetables in the *dambos* and (3) maize crop in the *dambos* on residual fertility on the vegetable plots without applying any external inputs to the land (Kuntashula et al. 2004). In adopting of coppicing fallows, such as *Gliricidia*, farmers can intensify their cropping systems, diversify crops grown and increase their incomes and nutritional needs.

9.4 Synthesis of Sustainability Indicators

9.4.1 Crop Productivity

Shade trees are often removed from the plantation once the cacao matures with the hope to reduce assumed competition and yield reduction. Contrary to this general belief, Abou Rajab et al. (2016) demonstrated that cacao bean yield does not necessarily decrease under a cover of *Gliricidia* shade trees. A cover of shade trees can harbour a more diverse fauna (Tscharntke et al. 2011) than cacao monocultures, and these diverse communities may provide natural pest control through the provision of niches for insectivorous birds, parasitoids and pest-feeding insects (Abou Rajab et al. 2016). The increase in pollinator fauna may also indirectly increase cacao bean yield by enhancing pollination services. A layer of shade trees can also reduce weed cover under the cacao trees and may minimize soil erosion after heavy rainfall (Rice and Greenberg 2000). Nutrient input through nitrogen fixation by *Gliricidia* is likely an important N source in the cacao-*Gliricidia* systems (Abou Rajab et al. 2016). Nutrient cycling and nutrient addition to the topsoil are increased by a higher above-ground litter mass and accelerated decomposition due to N-rich litter.

In a long-term experiment on an Alfisol at Ibadan (Nigeria), Kang et al. (1999) showed that alley cropping with *Gliricidia* sustains maize yield at moderate level (>2 Mg ha^{-1}), which was comparable with maize yield in sole cropping amended with 45 kg N ha^{-1} inorganic fertilizer. In alley cropping with *Gliricidia* on a semi-arid site in Kenya, maize yields were comparable with yields in continuously cropped sole maize in seven seasons, higher in one season and lower than in continuously cropped sole maize in four seasons (Rao and Mathuva 2000). Maize productivity increased by 27% in biomass transfer system, where green manure from *Gliricidia* was applied. However, this was not economical because of high labour costs (Rao and Mathuva 2000). In alley cropping in Sri Lanka, maize yields were significantly greater in rows in the middle of the alleys compared with the sole crop, suggesting complementary interactions from *Gliricidia* hedgerows through increased resource availability and/or more favourable microenvironment for the crop (Nissanka and Sangakkara 2008). In general, *Gliricidia* increased crop yields in most studies reviewed by Kang et al. (1998), although hedge effect off-set increases in some studies—the reduced yield due to shading by the hedgerows at the tree-crop interface.

With *Gliricidia*-maize intercropping, farmers can dramatically increase crop yields with or without additional inorganic fertilizer applications. Research conducted in Malawi and Zambia has shown doubling of maize yield with *Gliricidia*-maize alone and tripling with *Gliricidia*-maize + inorganic fertilizer amendments starting from 3 years after tree establishment (Akinnifesi et al. 2006). These productivity levels can be sustained for at least 15 years. According to a meta-analysis of 15 studies across SSA (Sileshi et al. 2010, 2014), yield increases with *Gliricidia*-maize intercropping over the control were 2.2 Mg ha^{-1} (2.0–2.4 Mg ha^{-1}), which was over 296% increase in percentage terms. Similarly, in meta-analysis of 4 studies, sorghum yields in *Gliricidia*-sorghum intercropping increased by 93.8% (Sileshi et al. 2014). The SOC and N that *Gliricidia* adds to the soil in intercropping are essential in maintaining soil fertility while reducing erosion and leaching of soil nutrients.

In a biomass transfer study in Central Malawi, Sileshi et al. (2011) showed a significant increase in fruit yield of paprika plants receiving *Gliricidia* biomass. Similarly, in two separate studies in Eastern Zambia, Kuntashula et al. (2004, 2006) demonstrated significant increases in yields of cabbage, onion and a subsequent maize crop during the dry season across 43 farmers. Net incomes derived from cabbage and onion grown using *Gliricidia* at 12 Mg ha^{-1} were also comparable with that from fully fertilized crops (Kuntashula et al. 2006).

9.4.2 Fodder Productivity

Gliricidia has high nutrient content, especially the total N (4.1%) and crude protein content (25.6%) (Chakeredza et al. 2007). In the dry season, fodder availability is crucial in sub-Saharan Africa when the natural vegetation dries or of poor nutritive value. The leaves can be dried and stored. *Gliricidia* can be used as a fodder supplement for cattle, goats and rabbit, but they are not suitable for pigs. In fish farming, some innovative farmers have found that surface application of *Gliricidia* leaves can improve the quality of fish ponds. In Zimbabwe, fodder production has been estimated at 3–5 Mg ha^{-1} year^{-1} at Domboshawa (high rainfall sites) and 2–6.3 Mg ha^{-1} year^{-1} at Makoholi (a low rainfall site) (Chakeredza et al. 2007).

9.4.3 Water Productivity

An important aim of agroforestry is to enhance biomass production on farms by increasing the productive use of water. In arid and semi-arid regions, crops productively utilize less than half of the annual rainfall, with the remainder being lost as run-off, evaporation or drainage. Therefore, water use efficiency is an important indicator of productivity and sustainability in agroforestry systems, particularly in rain-fed smallholder systems (Sileshi et al. 2011, 2012). Common metrics of water use efficiency include grain yield per mm of rainfall, often referred to as rain use efficiency (RUE) in rain-fed agriculture (Sileshi et al. 2012) and increase in crop yield due to irrigation per m^3 irrigation water applied ha^{-1} (Smith et al. 2017). In the present analysis, we will focus on the water uptake and RUE.

In a cacao agroforestry in Sulawesi, increased canopy cover from shade trees has been shown to enhance water uptake (Köhler et al. 2009). Stable isotope analyses confirmed that cacao and *Gliricidia* use soil water in a complementary manner, i.e. cacao trees mainly using water from the upper soil layer whereas *Gliricidia* shade trees use water from deeper soil layers (Schwendenmann et al. 2010). This is occasioned by the pronounced vertical root segregation between cacao and *Gliricidia* shade trees; cacao roots are concentrated in the upper profile while *Gliricidia* roots in the subsoil (Abou Rajab et al. 2016).

In alley cropping, competition for water was the main problem near the hedgerows, but competition for nutrients and light was less important (Lehmann et al. 1998). Between the hedgerows, alley cropping, often, results in a spatial separation of the root systems of trees and crops. For example, sorghum was found to have more roots in the topsoil and the *Gliricidia* trees having more roots in the subsoil (Lehmann et al. 1998). The spatial separation of the root systems has been reported to lead to complementary water use by the tree and sorghum crops on the semi-arid site in Kenya (Lehmann et al. 1998). The agroforestry combination used the soil water between the hedgerows more efficiently than either the sole tree stands or the sole sorghum crops. Soil water depletion was significantly lower in the topsoil between the tree rows than in any other position, and the soil water not used by the tree was utilized by the sorghum planted between the tree rows (Lehmann et al. 1998). Similarly, studies using stable isotopes ^{2}H or ^{18}O in Malaysia demonstrated that mature *Gliricidia* trees took up water from lower soil depths than maize (Zaharah et al. 2008).

Simulations using the APSIM (Agricultural Production Systems Simulator) Next Generation (Smethurst et al. 2017) and WaNuLCAS (water, nutrient and light capture in agroforestry) (Chirwa et al. 2007) demonstrated that *Gliricidia*-maize

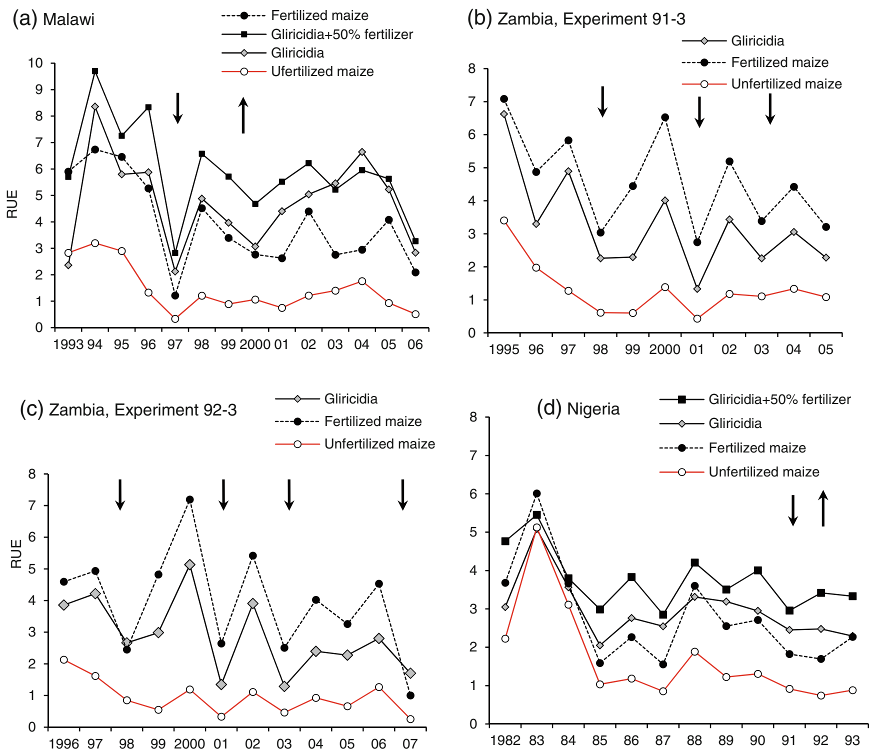

Fig. 9.2 Rain use efficiency (RUE in kg ha^{-1} mm^{-1}) by maize in *Gliricidia*-based agroforestry systems and monoculture maize in Malawi (**a**), Zambia (**b** and **c**) and Nigeria (d). Arrows pointing down indicate extremely wet conditions, while those pointing up indicate drought or extremely dry conditions during the maize-growing seasons

ensures more effective water availability and crop utilization than in sole maize in Malawi. In a more detailed analysis (see Case Study), *Gliricidia*-maize fields amended with 50% of the recommended fertilizer had consistently high RUE even in extreme rainfall or extremely dry years (Fig. 9.2). *Gliricidia*-maize intercrops supplemented with 50% fertilizer also had the lower inter-annual variability (CV = 30.2%) compared with *Gliricidia*-maize intercropping (mean 4.7; CV = 37.0%) and fertilized monoculture maize (mean 3.9; CV = 42.8%). On the other hand, the lowest RUE (1.5 kg ha^{-1} mm^{-1}) with the highest inter-annual variability (CV = 62.3%) was recorded in the farmers' practice of growing unfertilized maize.

Similarly, on two sites in Zambia (Fig. 9.2b, c), monoculture maize grown with the recommended dose of fertilizer was the most efficient in rainfall use (mean RUE 3.8–4.6; CV = 31.5–42.1%), closely followed by maize-*Gliricidia* intercrop (mean 2.9–3.3; CV = 41.6–45.9%). The lowest RUE with higher inter-annual variability (mean 0.9–1.3 and CV = 58.6–62.5%) was recorded in unfertilized maize. In Nigeria (Fig. 9.2d), RUE was high, where maize grown in *Gliricidia* alleys was supplemented with 50% of the recommended inorganic fertilizer (mean 3.8; CV = 20.6%). RUE remained high in this system even during the extremely wet conditions in the 1985, 1987 and 1991 cropping seasons. The lowest RUE with higher inter-annual variability was recorded in unfertilized maize (mean 1.7; CV = 75.0%).

9.4.4 Environmental Sustainability

In some of the long-term trials reviewed, data on changes in SOM (or SOC), soil N and P availability and uptake, carbon sequestration, GHG emission, erosion control and diversity of fauna were available. These were used as the main indicators of the environmental sustainability of *Gliricidia*-based agroforestry practices.

9.4.4.1 Soil Organic Carbon

The SOC content is considered as a "universal indicator" of soil fertility and a broader indicator of ecosystem response to environmental change (Loveland Webb 2003). The SOC pool is also the most reliable indicator for monitoring soil degradation (Lal 2015), and it is the most commonly employed metrics of sustainable intensification (Smith et al. 2017). The soil organic matter also serves to capture nutrients that can be made available for plant use.

In multistrata agroforestry, measured carbon stocks were higher in cacao-*Gliricidia* agroforestry (18 Mg C ha^{-1}) compared to cacao monoculture (11 Mg C ha^{-1}), where *Gliricidia* trees contributed 57% of the total biomass carbon (above- and below-ground) (Abou Rajab et al. 2016).

In a 19-year-old *Gliricidia* alley cropping in Costa Rica, the SOC pool was 16–23% higher than the sole crop (Oelbermann et al. 2004). In the 19th year of alley cropping, SOC was significantly higher in the alley crop (3.2%) than sole crop (2.4%) (Oelbermann et al. 2004). Similarly, in Sri Lanka, the addition of *Gliricidia* biomass and crop residues over 5 years improved SOM by 50–75% over initial soil condition (Nissanka and Sangakkara 2008).

At Makoka in Malawi, after 12 years soil C increased to 10 g kg^{-1} in the *Gliricidia*-maize intercrop from 8.8 g kg^{-1} at the commencement of the experiment in the 0–20 cm depth (Makumba et al. 2006). On the other hand, in the sole maize, soil C decreased to 5.5 g kg^{-1} after 12 years. The *Gliricidia*-maize intercrops stored 123–149 Mg C ha^{-1} over 10 years in the 0–200 cm soil via root turnover and pruning application in addition to 17 Mg C ha^{-1} stored in the tree stump and structural roots (Makumba et al. 2007). According to simulations using the Roth C model, soil C stocks increased by 29% (from 26.2 to 33.9 Mg ha^{-1}) in *Gliricidia-maize* intercropping over 10 years (Kaonga and Coleman 2008). The build-up of SOC in *Gliricidia*-maize intercropping is attributed to the repeated applications of pruning of high-quality biomass (Beedy et al. 2010) and root turnover (Makumba et al. 2007). Similarly, *Gliricidia* trees in pasture grass contributed 16–18 Mg C ha^{-1} to soil over 12 years (Sierra and Nygren 2006).

9.4.4.2 Soil Nutrient Availability and Uptake

9.4.4.2.1 Nitrogen Availability and Uptake

The contribution of *Gliricidia* to soil fertility, mainly, comes from N inputs via BNF and the deep capture of N (and other nutrients) by tree roots from soil depths beyond the reach of crop roots and transfer to the soil surface through litter fall, tree prunings and their decomposition. In Siri Lank, Jayasundara et al. (1997) estimated that N was fixed at 112 kg ha^{-1} yr^{-1}, of which 67% was N derived from the atmosphere (NDFA). In Eastern Zambia, Mafongoya et al. (2006) estimated N fixed by *Gliricidia* at 212 kg ha^{-1} yr^{-1}, while in Nigeria the estimated N fixed was 108 kg ha^{-1} yr^{-1}, of which 72% was NDFA (Danso et al. 1992). The amount of N fixed by *Gliricidia* trees and NDFA are comparable with values reported (Herridge et al. 2008) for common food legumes, such as soybean, groundnuts and beans (*Phaseolus vulgaris*).

In alley cropping with *Gliricidia* in Sri Lanka, the addition of tree biomass and crop residues over 5 years improved soil N content by 50–75% over the initial soil N (Nissanka and Sangakkara 2008). In the same experiment, the total ^{15}N recovery from *Gliricidia* biomass by the maize crop was 48% (about 25% in grain and 23% in residues) (Nissanka and Sangakkara 2008). Similarly, in alley cropping in Malaysia, leaf biomass from *Gliricidia* hedgerows contributed to 15% of the N taken up by maize (Zaharah et al. 2008).

In *Gliricidia*-maize intercropping in Southern Malawi, 298 kg N ha^{-1} year^{-1} could be realized from pruned biomass, and at approximately 20% N use efficiency, the N contributed by *Gliricidia* to maize was equivalent to 60 kg N ha^{-1} year^{-1} inorganic fertilizer (Akinnifesi et al. 2007). Further analysis by Dong-Gill (2012) showed that it was possible to reduce synthetic N fertilizer use by 48 kg N ha^{-1} yr.$^{-1}$ with *Gliricidia*-maize intercropping in Southern Malawi. At Msekera in Eastern Zambia, the fertilizer value of total N from the coppice biomass was estimated at 11–124 kg N ha^{-1} year^{-1}, with a mean of 61.4 kg N ha^{-1} year^{-1} (Sileshi and Mafongoya 2006). According to nutrient balance studies in Eastern Zambia (Mafongoya et al. 2006), *Gliricidia*-maize intercrop had a positive N balance due to BNF and deep capture of N from depth.

The N uptake by crops is also improved when cereals are associated with *Gliricidia*. For example, in alley cropping in Nigeria, N uptake by maize was 159.6% higher than sole maize (Okogun et al. 2000). Similarly, in Southern Malawi, N uptake was 156% higher in *Gliricidia*-maize intercropping than sole maize (Mweta et al. 2007). In Eastern Zambia, N uptake by maize was 160% higher in *Gliricidia*-maize intercropping compared to the unfertilized sole maize and 32% higher than fully fertilized sole maize (Mafongoya, unpublished data).

9.4.4.2.2 Phosphorus Availability and Uptake

Gliricidia adds substantial amounts of P inputs through coppice biomass. The amount of P applied through coppice biomass averaged 21 kg P ha^{-1} year^{-1} in *Gliricidia*-maize intercropping at Makoka in Southern Malawi (Akinnifesi et al. 2007). Similarly, the mean fertilizer value of total P from the coppice biomass were estimated at 4.5 kg P ha^{-1} year^{-1} in *Gliricidia*-maize intercropping at Msekera in Zambia (Sileshi and Mafongoya 2006).

The addition of organic inputs can increase P availability and uptake by reducing P sorption in the soils. In *Gliricidia*-maize intercropping in Southern Malawi, the addition of pruned biomass and inorganic P application significantly reduced P sorption capacity of the soil (Mweta et al. 2007). *Gliricidia*-maize intercropping also increased P uptake by maize by 121% in Malawi. In Eastern Zambia, P uptake was 92% higher with *Gliricidia* than unfertilized sole maize but 1–8% lower than fully fertilized sole maize (Mweta et al. 2007).

9.4.4.3 Erosion Control

Soil organic matter helps bind soil particles together, which reduces erosion. The trees will also help protect the soil from wind and rain that can carry topsoil off the site. Trees can increase root biomass, with knock-on positive effects for soil stabilization and reduction of soil erosion. Above-ground plant parts and roots combine to protect the soil against erosion by physically sheltering and fixing soils, offering resistance to rain, run-off (Sileshi et al. 2014). Fine roots physically bind together soil particles, particularly clay and silt. Trees can also lead to improvement in soil structure, which increases drainage. The improvement of soil structure result from the large quantities of litter fall, root biomass, root activity, biological activities and roots leaving macropores in the soil following their decomposition (Sileshi et al. 2014). As such, root biomass, infiltration rates and time to run-off were used as good indicators for judging *Gliricidia*-based agroforestry practice.

9.4.4.4 Soil Biota and Biological Activity

Important biota in *Gliricidia*-based agroforestry practices range from rhizobial symbionts to mycorrhizal fungi, other soil bacteria, fungi and macrofauna. The contribution of *Rhizobia-Gliricidia* associations to building up N in degraded soils through BNF is an important ecosystem service provided by soil biota.

Arbuscular mycorrhizal fungi (AMF) associated with trees can complement the nutrient capture function of deep roots by simultaneously increasing the recovery of nutrients from the subsoil, reduce nutrient loss through leaching and increase uptake of less mobile nutrients like P (Barrios et al. 2012).

Sileshi and Mafongoya (2006) compared the population of various soil macroinvertebrates in *Gliricidia*-maize intercropping with monoculture maize. In five separate experiments conducted at Msekera and Kalunga, the number of invertebrate orders per sample and the total macrofauna recorded were higher under *Gliricidia-maize* than under fully fertilized monoculture maize (Sileshi and Mafongoya 2006).

9.4.4.5 Carbon Sequestration Rates and GHG Mitigation

For agroforestry practices to be environmentally sustainable, energy inputs for crop management, including N fertilizer use, should be minimized to reduce emissions of GHGs including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). This is particularly so for N_2O emissions because the global warming potential of N_2O is 265 times that of CO_2 (Epie et al. 2015). In Indonesia, carbon sequestration rates were higher in cacao-*Gliricidia* agroforestry (13 Mg C ha^{-1} yr^{-1}) than cacao monoculture stands (9 Mg C ha^{-1} yr^{-1}), but the rates (18 Mg C ha^{-1} yr^{-1}) were significantly lower than Cacao grown under multiple species of shade trees (Abou Rajab et al. 2016).

In the *Gliricidia*-maize intercrop at Makoka, the annual net gain was 3.5 Mg C ha^{-1} year^{-1} in the soil (Dong-Gill 2012). With a potential for N_2O mitigation of 0.12–1.97 kg N_2O–N ha^{-1} year^{-1}, the *Gliricidia*-maize intercropping was estimated to mitigate 3.5–4.1 Mg CO_2 equivalents ha^{-1} year^{-1} (Dong-Gill 2012). The long-term mitigation potential of *Gliricidia*-maize intercropping was estimated using the Small Holder Agriculture Monitoring and Baseline Assessment (SHAMBA) framework across sites in Malawi using input data from the Malawi Agroforestry Food Security Program. The GHG emission/removal potentials was estimated over a 20-year period relative to the baseline of conventional maize cultivation, where crop residues are removed and burnt, and fields are left bare during the dry season. The net removal using *Gliricidia*-maize intercropping was −33 Mg CO_2 eq ha^{-1} (credible interval: −27 to −47 Mg CO_2 eq ha^{-1}) over 20-year period. However, the net removal widely varied with sites, the highest being at Makoka (−74 Mg CO_2 eq ha^{-1}), followed by Karonga (−40.5 Mg CO_2 eq ha^{-1}) in the Northern Malawi, Salima (−39.3 Mg CO_2 eq ha^{-1}) in Central Malawi, Zomba (−34.7 Mg CO_2 eq ha^{-1}), Machinga (−33.7 Mg CO_2 eq ha^{-1}) and Mulanje (−31.1 Mg CO_2 eq ha^{-1}) in Southern Malawi (Nicholas Berry, unpublished).

Compared with the conventional maize cropping systems, *Gliricidia*-maize intercropping also used less or no synthetic N fertilizer and may have the potential to mitigate CH_4 emissions. According to a recent global synthesis (Kim et al. 2016), soils under agroforestry oxidized 1.6 kg of CH_4 ha^{-1} yr^{-1}. The greater CH_4 uptake is probably related to greater soil pore space and reduced soil bulk density under agroforestry compared with agricultural fields (Kim et al. 2016).

Fertilizer use accounts for a large portion of N_2O emissions from agricultural soil (Inselsbacher et al. 2011). N_2O emission is mainly driven by the availability of N and soil water-filled pore space of 60–90%, which more frequently occurs in humid tropical regions and in savannas during the rainy season (Castaldi et al. 2006; Valentini et al. 2014). In arid and semi-arid areas, conditions are generally limiting for the significant N_2O production (Valentini et al. 2014). Some of the N from inorganic fertilizer and legume biomass not taken up by plants and microbes in the soil can contribute to N_2O emissions (Hall et al. 2006), especially after rainfall events. On the one hand, in a semi-arid condition in Mali, Hall et al. (2006) found six times more N_2O emission from *Gliricidia* plots than continuous cultivation of sorghum without fertilizer. On the other hand, in a wet tropical soil, Seneviratne and Van Holm (1998) found over 5900 times more N_2O emission from soil without mulch than from plots that received *Gliricidia* mulch. In the same experiment, N_2O emission from urea fertilizer was over 25,000 times more than from plots that received *Gliricidia* mulch (Seneviratne and Van Holm 1998). 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 N_2O ha^{-1} $year^{-1}$, the *Gliricidia*-maize intercropping in Malawi was also estimated to mitigate 3.5–4.1 Mg CO_2 eq. ha^{-1} $year^{-1}$ (Kim 2012).

9.4.4.6 Weed and Pest Control

A growing body of literature suggests linkages between declining soil fertility, pest damage and weed problems in agroecosystems. For example, the extent and intensity of witchweed (S*triga* spp.) infestations depends largely on the fertility status of the soil (Sileshi et al. 2006). According to a study in Eastern Zambia, both the quantity and quality of biomass produced by the agroforestry species affect the incidence and abundance of the witchweed (Sileshi et al. 2006). *Gliricidia* was found to be effective in reducing witchweed abundance relative to a fully fertilized monoculture maize (Sileshi et al. 2006), which was attributed to the continuous applications of organic matter, which improves soil fertility and suppresses the germination and growth of weed seeds. In addition, *Gliricidia*-maize intercropping significantly reduced the total biomass as well as the abundance of both grass and broad-leafed weeds compared to fully fertilized monoculture maize in Eastern Zambia (Sileshi et al. 2006). This is probably because *Gliricidia* can shade out arable weeds that compete with maize for water and nutrients.

Gliricidia-maize intercropping has also been demonstrated to reduce termite damage to maize compared with monoculture maize (Sileshi et al. 2005). The decrease in termite damage in *Gliricidia*-maize intercrops is attributed to the improvement in SOM and soil water retention. Termites feed on crop residues, mulches and soil organic matter. However, when this type of food is not available, they will eat live plants including maize, and their damage is known to be more in soils with low organic matter content. Termites rarely attack healthy plants but may do so following the weakening of plants due to moisture stress, low soil fertility or neglect of cultural practices. Since *Gliricidia* improves soil fertility and reduces moisture stress in maize, naturally, termite damage will be lower.

9.4.5 Economic Sustainability

Although intercropping with *Gliricidia* requires increased input in labour, it demands limited financial investment as opposed to the use of inorganic fertilizers. The yield benefit can also reduce the labour cost significantly. Reduced labour in weeding due to smothering effect of shading on major weeds is also an additional benefit (Sileshi et al. 2006). Contrary to the popular notion that *Gliricidia*-based agroforestry practices are more labour intensive, analyses conducted in Eastern Zambia (Ajayi et al. 2009) demonstrated that over 5-years period, on average farmers used 519 labour days in *Gliricidia* fields compared with 532 labour days fertilized monoculture maize fields. Very little labour is used in *Gliricidia* fields in the second year after the establishment of trees and before the trees are cut in the third year. In terms of returns to land and labour, the net present values (NPV) and benefit cost ratios (BCR) show that *Gliricidia*-maize intercropping was comparable or better than monoculture maize grown with inorganic fertilizer. With a net present value (NPV) of \$499 ha^{-1} over a 5-year cycle, subsidized fertilizer (at 50% government subsidy) was financially the most profitable option. Without government subsidy, fully fertilized maize gave NPV of \$349 ha^{-1}, while *Gliricidia*-maize intercropping gave NPV of \$327 ha^{-1} over 5-year cycle in Eastern Zambia (Ajayi et al. 2009). In terms of BCR, *Gliricidia*-maize (BCR: 3.1) even performed better than the recommended fertilizer purchased at market price (BCR: 1.8) in Eastern Zambia (Ajayi et al. 2009).

Vegetable crops and maize can be produced using biomass transfer using *Gliricidia*. This has been studied well in Eastern Zambia, where vegetables are grown with *Gliricidia* biomass and green maize is produced using the residual soil fertility. On the one hand, Kuntashula et al. (2004) estimated net incomes of US\$7728 ha^{-1} and US\$9700 ha^{-1} from cabbage grown using *Gliricidia* 8 Mg ha^{-1} and *Gliricidia* 12 Mg ha^{-1}, respectively. On the other hand, the net incomes from cabbage grown with inorganic fertilizer and no input (control) plots were US\$10,378 ha^{-1} and US\$2714 ha^{-1}, respectively. In the case of onions, the net incomes were estimated at US\$4100, US\$3260 and US\$2090 ha^{-1} with *Gliricidia* 12 Mg ha^{-1}, *Gliricidia* 8 Mg ha^{-1} and inorganic fertilizer, respectively. Net incomes from the no input control were estimated at only US\$165 ha^{-1}.

The effects of *Gliricidia* biomass persist beyond the maturity of most vegetables, and, thus, a green maize crop can be produced on the residual soil fertility (Kuntashula et al. 2004, 2006). The lowest and highest net incomes from green maize produced following cabbage were obtained in the no input control (US\$855 ha^{-1}) and *Gliricidia* 12 Mg ha^{-1} (US\$1740 ha^{-1}), respectively. The net income obtained from fully fertilized maize was US\$1381 ha^{-1}. The high-value vegetables and the green maize (which is more valued than the dry grain) increase farmers' income. Randomized controlled experiments conducted in 2003 in Eastern Zambia showed only slight differences in gross margins obtained from the recommended inorganic fertilizer and the 8 Mg ha^{-1} *Gliricidia* biomass treatment (Kuntashula et al. 2004, 2006). The major costs for the fertilizer treatment were cash, while for the *Gliricidia* biomass treatment, the major cost was labour. Over all, the inorganic fertilizer treatment required higher cash costs than the *Gliricidia* biomass treatment (Fig. 9.3). This cost structure highly favours resource-poor farmers with sizeable amounts of family labour, which, in most parts of rural Africa, has a lower opportunity cost.

The foregoing shows that a substantial amount of income can be obtained from *Gliricidia* biomass transfer in vegetable gardens. Generally, the net incomes of the biomass transfer technologies are substantially reduced by the labour costs for pruning and incorporation of the biomass. Where the opportunity cost of labour is very low like in most SSA, the labour constraint could easily be done away with.

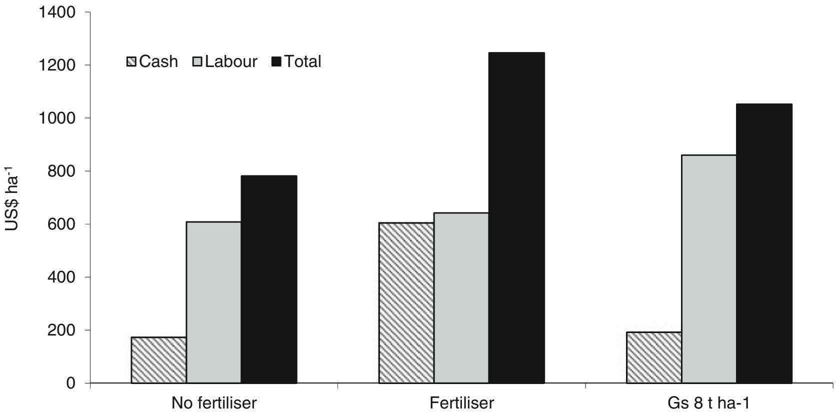

Fig. 9.3 Cabbage production costs using various options in Eastern Zambia in 2003

9.5 Case Studies

9.5.1 Inter-Annual Variability in Yield

At the Makoka site, the highest yield (4.9 Mg ha^{-1}) with the lowest inter-annual variability (CV = 24.8%) was recorded in maize-*Gliricidia* intercrops amended with 50% of recommended fertilizer. The average yields and inter-annual variability in maize-*Gliricidia* intercrops (3.9 Mg ha^{-1}; CV = 27.1%) were comparable with those in fully fertilized monoculture maize (3.1 Mg ha^{-1}; CV = 27.9%). The low yield relative to the 14-year average was recorded in most treatments during an extremely wet years (Fig 9.4a–c) and dry years (Fig. 9.4a and d).

The farmer practice of growing unfertilized maize was particularly vulnerable to extreme rainfall, while *Gliricidia*-diversified treatments generally gave higher yields. Grain yield in unfertilized maize was negatively correlated ($r_s = -0.64$, $p < 0.01$) with the total precipitation during the growing season. In contrast, yields in maize-*Gliricidia* intercrops were positively correlated with rainfall. Grain yield in fertilized monoculture maize was significantly negatively correlated with rainfall during physiological maturity ($r_s = -0.54$, $p < 0.05$).

Trends in relative yields were significantly positive in maize-*Gliricidia* intercrops ($R^2 = 0.398$; $p = 0.016$), maize-*Gliricidia* intercrops amended with 50% fertilizer ($R^2 = 0.577$; $p = 0.002$) and fully fertilized monoculture maize ($R^2 = 0.432$; $p = 0.011$) at Makoka. The *Gliricidia*-maize intercropping seems to offer an insurance against crop failure in unfavourable years and an increasing bonus crop as years get more favourable. If short season and drought-tolerant varieties of cereal crops become available, *Gliricidia*-based agroforestry practices can offer a more promising climate change adaptation strategy than cereal monoculture in the resource-limited areas of SSA. In SSA, where most farmers have limited access to

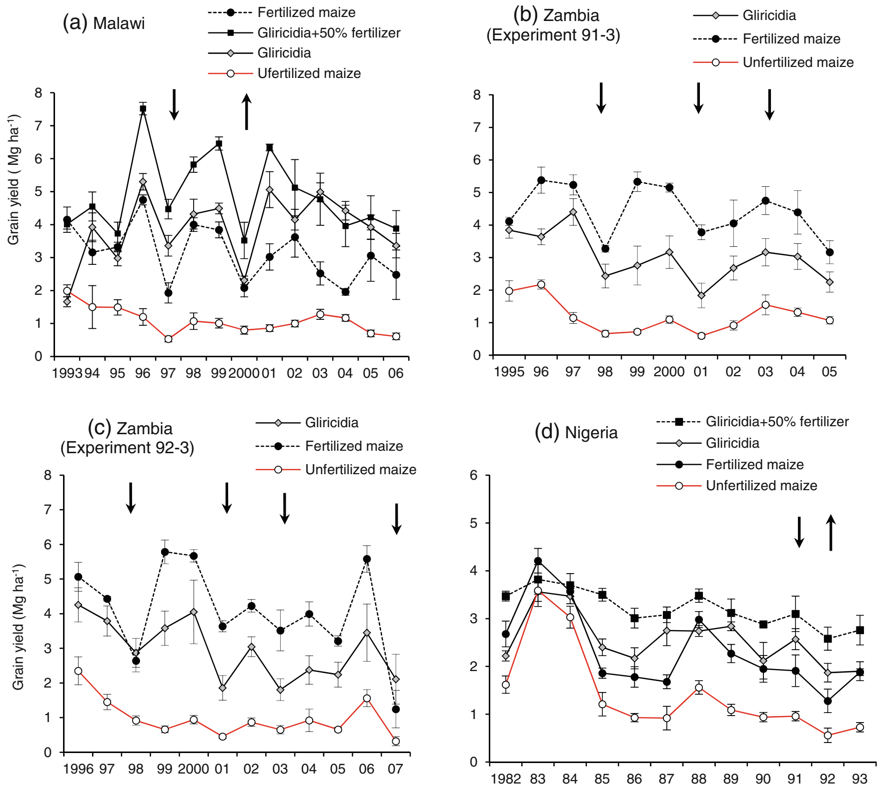

Fig. 9.4 Maize grain yield (Mg ha^{-1}) in various maize production systems in Malawi (**a**), Zambia (**b** and **c**) and Nigeria (**d**). Arrows pointing down indicate extremely wet conditions, while those pointing up indicate drought or extremely dry conditions during the maize-growing seasons. Error bars represent standard errors

inorganic fertilizers, the reduced fertilizer requirement in *Gliricidia*-based agroforestry systems is a great help in saving on investment in synthetic fertilizer inputs. Even in conditions where farmers can afford synthetic fertilizers, the reduced need for N fertilizer can potentially cut N_2O emissions from nitrogen fertilizers. Therefore, when strategically integrated with cereal crops, *Gliricidia* can also reduce yield variability, production risks and greenhouse gas emissions.

9.6 Conclusions and Recommendations

Taken together, the results above demonstrate that the *Gliricidia*-based agroforestry practices are sustainable over the long-term compared with crop monocultures. The various *Gliricidia*-based practices performed well when judged against the key indicators of sustainable intensification under productivity, economic and environmental sustainability and human well-being. It is also concluded that *Gliricidia*-based practices meet the central requirements for agroforestry in resource-limited agroecosystems, i.e. that the trees (1) can acquire resources that associated crops would not otherwise get, (2) have positive effects on crops, (3) ensure more closed nutrient cycling and (4) enrich the soil with organic matter and nutrients.

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Socio-Economic and Policy Issues in Relation to the Adoption of Agroforestry in Africa

10

Cliff S. Dlamini

Abstract

Agroforestry is not new in Africa, and different traditional and modern technologies, practices and systems of agroforestry are found in African countries. Despite the introduction of monoculture annual crops, a significant proportion of smallholder farmers (and rural households and communities) in sub-Saharan Africa (SSA) have persisted with practicing agroforestry in the drylands of Southern Africa, East Africa, West Africa and Central Africa. Multi-purpose trees are grown for a variety of direct and indirect use as well as intermediate uses in both cropped lands and pastures. Based on the critical review, synthesis and analyses of agroforestry studies, several pertinent issues related to agroforestry development have been discussed. Further, the stakeholders that influence the adoption of agroforestry systems among smallholder farmers in Africa face challenges and opportunities. Challenges include lack of understanding of the benefits and advantages of agroforestry, delayed return on investment and underdeveloped markets, market constraints, focus of agriculture on using fertilizers and pesticides, emphasis on commercial agriculture, lack of land tenure rights among smallholder farmers, lack of coordination among sectors, adverse regulations, lack of quality tree seed supplies, lack of sufficient extension work, lack of skill, knowledge and awareness as well as farm and farmer characteristics. Opportunities entail contextual drivers, prevailing conditions and institutions influencing the trends in agroforestry development. Internal capacities are critical to ensure that agroforestry development is driven by various stakeholders and early adopters. Further, enabling economic and institutional policies are crucial in advancing agroforestry. Most importantly, agroforestry thrives where it is beneficial to farmers and security of

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tenure rights is important. The adherence to norms and strict enforcement of forest management rules is essential for the success of agroforestry at different spatial scales.

Keywords

Traditional and modern technologies · Social issues · Economic aspects · Institutional issues · Adoption of agroforestry

10.1 Introduction

Agroforestry is not new in Africa, and many traditional and modern practices and systems are found throughout the region. Despite the introduction of monoculture annual crops, a significant proportion of smallholder farmers and rural households and communities in sub-Saharan Africa have persisted with practicing agroforestry (Mbow et al. 2014a). Multipurpose trees are grown for a variety of direct and indirect use benefits on both cropped lands and in pastures (i.e. livestock grazing systems) (Jama and Zeila 2005). Other common forms of agroforestry include tree crops, like oil palm and rubber trees, and the traditional migratory slash-and-burn agriculture, the latter being of a sequential kind (Cook and Grut 1989). In recent times, it has been found that African agroforestry systems have the ability to improve the resilience of local communities and households towards undesirable impacts of climate hazards such as wild fires, drought, floods and flash floods, extreme heat and shorter rainy seasons (World Agroforestry Centre 2008; Ofori et al. 2014). Currently, agroforestry is one of the few land management options that promise synergies between food and nutrition security and climate change adaptation and mitigation (Mbow et al. 2014b). However, such synergies are possible if appropriate methodologies, improved qualitative data and supportive policy environments allow for the successful scaling-up of agroforestry systems in Africa (FAO 2011, 2013a). Most importantly, it is worthy to note that the full potential of agroforestry to respond to poverty and food insecurity and global climate change cannot be fully realized until the constraints and various challenges to scaling-up agroforestry are addressed and ultimately resolved. It becomes imperative for developing countries, especially in Africa, to develop, formulate and implement national agroforestry strategies, so that agroforestry is considered a part of the national development agenda.

10.2 Issues in African Agroforestry

Based on the review and synthesis of agroforestry studies in preceding sections, several critical issues can be raised as pertinent to agroforestry development for enhancing livelihood security in Africa. On the basis of the work of Cook and Grut (1989) and Dlamini (2019), these may be grouped into five categories—(1) technical issues, (2) economic issues, (3) social issues, (4) institutional issues and (5) research issues – and briefly discussed as follows:

10.2.1 Technical Issues

10.2.1.1 Criteria for Species Selection

In terms of species selection for agroforestry, it is advisable to adopt the following options:

1. Considering the fundamental principles of tree improvement and the significant role of genetic diversity in species adaptation, the option of using indigenous tree/shrub/plant species is preferred to importing alien or exotic species of trees and shrubs in Africa.
2. Multipurpose trees are more acceptable than single-purpose trees, in view of the multiple ecosystem functions that they stimulate, as well as the vast array of ecosystem goods and services they provide that have direct benefits to people and the environment.
3. In view of the challenges of unprecedented environmental and climate change risks, fast-growing early maturing trees/shrubs (e.g. fruit trees) are preferred to trees that have a long maturity period in agroforestry. This serves as a unique climate change adaptation strategy.

Thus, fast-growing non-native tree species represent the majority of trees planted in tropical agroforestry systems (Cook and Grut 1989; Koskela et al. 2010; Foster and Neufeldt 2014). Further, Ofori et al. (2014) suggested a move towards developing more innovative and highly productive agroforestry systems in Africa. In addition, adopt and apply tree improvement principles to establish tree domestication programmes in the same way coffee, cocoa, kola nut and rubber trees were domesticated, in a bid to improve household food and nutritional security. Based on the species selection criteria for agroforestry that is presented above, Box 10.1 highlights examples of common and/or preferred species for domestication and commercialization in Africa. Most importantly, all these species are indigenous and have been considered important for domestication in sub-Saharan Africa (www.worldagroforestry.org/resources/databases/agroforestree, accessed on 12-01-2019).

Box 10.1 Some Indigenous Food Trees Species Considered for Agroforestry in sub-Saharan Africa

Baobab: The edible white, powdery pulp found in the fruit of *Adansonia digitata* is very rich in vitamins C and B2. Young leaves are rich in vitamin C and are in high demand in West Africa as a soup vegetable.

(continued)

Box 10.1 (continued)

Ber: The fruit of *Ziziphus mauritiana* is eaten fresh or dried and can be made into a floury meal, butter or a cheese-like paste and is a good source of carotene, vitamins A and C and oils. Also, large-fruited cultivars are found in Asia.

Bush mango: The fruit mesocarp of *Irvingia gabonensis*, sweet bush mango, is appreciated as a fresh fruit snack. Ground kernels of *I. gabonensis* and *I. wombolu* Vermoesen are used to thicken and flavour soups.

Desert date: The fleshy pulp of *Balanites aegyptiaca* fruit is eaten dried or fresh, and oil from the kernel is used for cooking and cosmetics. Young leaves and tender shoots are used as vegetable.

Marula: The fruit pulp of *Sclerocarya birrea* is used to produce jam, juice, beer and, in South Africa, the liqueur Amarula Cream, while the oily kernels are consumed raw, roasted and in sauces.

Njansang: A spicy sauce made from the kernels of *Ricinodendron heudelotii* is widely used in stews, and the high oil content of the seeds makes them suitable for use in the soap industry.

Safou: Extensively sold in local markets in Central and West Africa, *Dacryodes edulis* fruits are rich in vitamins and amino acids and eaten boiled or roasted.

Star apple: The fleshy and juicy fruits of *Chrysophyllum albidum* are popularly eaten and can be fermented and distilled for the production of wine and spirits.

Tamarind: The fruit pulp of *Tamarindus indica* is used to prepare juice and jam and is an ingredient in curries, chutneys and sauces. The ripe fruits of "sweet" types are eaten fresh as a snack.

Wild loquat: The fruit of *Uapaca kirkiana* is highly regarded and eaten fresh as well as used to prepare jams and beverages. Harvesting of fruit from the wild is an important coping strategy during famine.

Source: Ofori et al. (2014).

Other technical considerations that would determine the success of agroforestry include:

1. Availability of land and water (frequent drought is a reality).
2. Choice between passive (outdated) and active (current and relevant) agroforestry systems.
3. System complexity and management skill requirements (modern agroforestry requires scarce skills, technology and finance).

10.2.2 Economic Issues

Economic issues for consideration in making right choices about agroforestry will include the following:

1. Costs and benefits of agroforestry interventions (cost of agroforestry is lower than that of agriculture).
2. Smallholder perceptions of opportunity costs (opportunity costs of a new activity in relation to their entire array of farming and off-farm activities).
3. Supply-led versus demand-led project designs (need for market-led community commercialization).
4. Inadequate understanding of local markets (several intermediaries are involved before a product reaches its final consumer).
5. Connection with off-farm enterprises and employment (income diversification).
6. Private returns versus public objectives (issue of social profits vs financial profits).

10.2.3 Social Issues

Social issues in agroforestry for African communities are rather complex as determined by the different cultures and traditions between households with communities, between communities within states and between states within subregions, which are summarized as follows:

1. Differential adoption of agroforestry by gender, age, and socioeconomic level.
2. Pastoralists and agroforestry (relations between nomadic and settled populations are very complex).
3. Tree tenure, land tenure and usufruct rights (ownership or secure use of land is frequently cited as a precondition for farmers to make long-term investments in agriculture).

10.2.4 Institutional Issues

In the ongoing global sustainable development dialogue and the implementation of the 17 sustainable development goals (Vision 2030), the most critical factor of sustainability depends on effective and efficient institutional frameworks and appropriate institutional arrangements. The same applies for agroforestry development in Africa. Some institutional issues for the adoption of agroforestry relate to:

1. Institutional design and project sustainability (adequate institutional design and long-term sustainability).
2. Institutional support for agroforestry interventions (services).

3. Use of local NGOs/community-based organizations (embedded in local social structures).

10.2.5 Research Needs

Although substantial agroforestry research has been undertaken in Africa, the following areas of research need to be strengthened.

1. Diagnostic studies and adaptive research: Needed to identify and better understand indigenous agroforestry systems, including both traditional systems and more recent adaptations to changing environmental conditions. However, there is a growing evidence that it is increasingly becoming difficult to predict future climate scenarios, and prediction models come with advantages and challenges as presented in Table 10.1.
2. Research delivery system: Research should be responsive to demands from the farm level and supported by a highly effective extension technique.
3. Using the "household" as the unit of data collection and analysis: focusing on a household as the sole unit of data collection and analysis can be misleading.
4. The many meanings of success: The definition of "success" in agroforestry has multiple dimensions. What may be appropriate, and apparently successful, from a technical viewpoint may be less successful from an economic, social, institutional or management perspective.

10.3 Factors Influencing the Adoption of Agroforestry among Smallholder Farmers in Africa

10.3.1 Challenges

10.3.1.1 Analysis of Constraints to Scaling-up or Wider Implementation

Several studies have been conducted in Africa solely on adoption or scaling-up or development of traditional and modern agroforestry technologies, practices, methods and systems. A number of factors have been identified as challenges or constraints. Some key factors that constraint the scaling-up of agroforestry are discussed as follows:

10.3.1.1.1 Lack of Understanding of the Benefits and Advantages of Agroforestry

Academia, farmers, extension staff, NGOs, the private sector and governments (policymakers) have a common tendency to over-rely on conventional agriculture systems (monoculture cropping) to the detriment of traditional and modern agroforestry systems. The public sector extension services lack sufficient on the relevant

Table 10.1 Advantages and challenges of climate change prediction models for adapting agroforestry systems

Advantages and challenges of climate change projection methods			
Method	Process-based modelling	Species distribution modelling	Climate analogue analysis
Advantages	• Understanding of system processes • Performance projection possible • Can be used in large-scale models	• Only location data needed • Several robust methods exist • Suitability maps can be used for making recommendations	• No prior information needed • Exploration of impacts in real-world context • Facilitates identification of adaption options
Specific challenges	• Understanding of tree-crop interactions • High data requirement • Model complexity compounds error sources • Modelling of all relevant system components with sufficient accuracy • Temporal downscaling of climate projections	• Availability of distribution data • Sampling bias • Availability of environmental data at appropriate resolution • Subpopulations with distinct habitat requirements? • Reliability when dealing with novel climates	• Identification of relevant climate metrics for analogue search • Non-climatic factors make many analogues useless • Collaborative/ ensemble methods are very costly • Only provides specific projections for individual sites • Reliability when dealing with novel climates
General challenges	• CO_2 impacts difficult to foresee (including only possible in process-based models) • Future climates are uncertain; ensemble projections are needed • Biotic factors (pests, weeds and diseases) are difficult to project		

Current opinion in environmental sustainability
Source: Mbow et al. (2014a)

skills, knowledge and understanding of agroforestry technologies. As a result, the multiple functions and multiple benefits of agroforestry systems are not well understood. The ranking of agriculture's contribution to the GDP and the exclusion of the potential financial and economic value of agroforestry in the system of national accounts favour agriculture over agroforestry, unless there is a paradigm shift. Agroforestry trials are mainly confined to research stations and not diffused to farmers (Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014). As of the 1990s, only a few extension projects in Africa had evaluated the financial impact of agroforestry or attempted to quantify its contribution to household income, food security and welfare (Franzel and Scherr 2002a).

10.3.1.1.2 Delayed Return on Investment and Underdeveloped Markets

The turnaround period for most agriculture crops is shorter and return on investment is quicker, while investing in agroforestry may come with disadvantages. However, this argument can be countered by the fact that horticultural crops in conventional (especially fruit trees) and timber species in plantation forestry systems also take extended periods before they reach the market. But still government policies favour more investment in those sectors than agroforestry. This is more a matter of understanding on the resource economics of the products provided by these sectors. Clearly, the net present value of agroforestry trees compared to establishment costs is superior to agricultural crops. The cost of the long-term environmental damage caused by agriculture crops due to tillage, application of inorganic chemical fertilizers and excessive use of water is unbelievable. Further, market information systems in most African countries do not include agroforestry trees (Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014). However, old studies on profitability analyses that were carried out in Southern Africa region show that the various agroforestry technologies are profitable relative to conventional production practices where trees are not grown (Ajayi et al. 2006).

10.3.1.1.3 Market Constraints

Market constraints play a significant role in hindering the scaling-up of agroforestry. The lack of market-led community commercialization approach has led to agroforestry extension and research emphasize, increasing production levels of trees and crops. But these efforts have been undertaken with little regard for demand and price. Research work has shown that market conditions and institutions play a critical role in farmer adoption of agroforestry (Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014).). For example, Franzel and Scherr (2002b) found that when the price of maize in Zambia decreased, farmers were more likely to use improved fallows to reduce the area under maize cultivation, allowing them to increase the production of higher value cash crops on other fields. In addition, market instability also affects agroforestry strategies, e.g. in Kenya when the milk industry became unstable, farmers replaced dairy meal with farm-grown *Calliandra* species. Its low cost reduced both their operating costs and their risk in a fluctuating market. Further, Franzel and Scherr (2002b) found that, the price of fuelwood had a strong effect on the popularity of agroforestry in Western Kenya.

10.3.1.1.4 Focus of Agriculture Using Fertilizer and Pesticides

Large-scale agriculture (dominated by monoculture cropping systems) has been in the mainstream since the 1960s at the expense of scaling-up agroforestry systems. It is inevitable to start demonstrating the potential of large-scale agroforestry in Africa. Billions of dollars are spent promoting agriculture, and this comes with excessive use of inorganic chemical fertilizers, pesticides and other chemicals. Despite the immediate improvement of soil fertility and increase in crop and livestock production in the short- and midterm, the fertilizers and pesticides have continued to pollute and degrade farmlands and the environment for many decades. The cost of environmental pollution is immeasurable, while rehabilitation of degraded lands and polluted ecosystems is a nightmare. Nonetheless, donors and governments have prioritized agricultural development programmes to increase access to fertilizers and pesticides at the expense of agroforestry and eco-agriculture. The subsidization of agriculture is the greatest challenge to scaling-up agroforestry (Franzel and Scherr 2002b; Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014; Mkonda and Xinhua 2017).

10.3.1.1.5 Emphasis on Commercial Agriculture

The policy and legislative framework in African states supports agriculture and somehow discourage farmers from adopting the available agroforestry options in various agroecological regions. Massive incentives are channelled to monoculture agriculture systems, and tax exemptions are directed to commercial agricultural production. Development finance is targeted at mainstream agriculture development, and the credit facilities in place to support agriculture have negative consequences on the scaling-up and development of any form of viable agroforestry. In other regions of the world, policies continue to discourage the development and scaling-up of agroforestry, for example, in Brazil. The government offers sizeable tax cuts to farmers producing biofuels as long as there is evidence that a portion of the raw material (feedstock) is obtained from smallholders, whether it is from agriculture or agroforestry systems. As a result, similar incentives and subsidies have led to a rapid extension of oil palm plantations in massive areas within the famous Brazilian Amazon. Favourable credit terms granted for large-scale monoculture systems are hardly ever offered to agroforestry initiatives. Hence, by excluding agroforestry in the benefit package, the system is discouraged. In Southern Africa, Zambia and Malawi are good examples of countries where agriculture input subsidies (for seeds and fertilizer) become a disincentive for farmers to adopt and practice sustainable agroforestry systems, which are not subsidized (Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014).

10.3.1.1.6 Lack of Land Tenure Rights Among Smallholder Farmers

The hierarchy of laws of natural resources, pollution and land use planning in African states is ambiguous. Land policies are fuzzy and riddled with unclear and/or complex land and tree tenure rights. Property rights, i.e. ownership and user rights, are unsecure and complex. Thus, at the farm level, the most concerning institutional arrangement discouraging the development of agroforestry is the issue of property rights. Property rights shape the farmers' expectations of whether and how they will be able to appropriate long-term benefits from investing in tree management and planting. Studies in Cameroon, Kenya, Mali, Uganda and Zambia revealed that the tenants without long-term land rights are stifled in their ability to engage in the long-term tree planting because of insecurity of tenure (Mercer 2004; Place 1994; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014).

10.3.1.1.7 Lack of Coordination Between Sectors

Agroforestry cuts across multiple sectors, i.e. agriculture, forestry, livestock, rural development, environment, energy, health, water and commerce, and thus often becomes the subject to policy conflicts and adverse incentives that work against its development. In many African states, the principle is that agroforestry cuts across all sectors, yet in reality, it belongs to none and rarely occupies a special line in a governmental body. Most of the times, agroforestry falls among the departments of agriculture, forestry and environment, with no institution taking a lead role in the advancement of agroforestry or its integration. Agriculture policies often undermine agroforestry. Therefore, in order to promote agroforestry, harmonization and synchronization of policies and programmes require a combination of policy reforms (review) across the various departments in charge of rural development, land use, agriculture, forestry, environment, finance and commerce at both national and local levels (Mercer 2004; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014).

10.3.1.1.8 Adverse Regulations

Overarching legislation and multiple legal restrictions on multifunctional land management and complex taxation policies may hinder the development of agroforestry. The agriculture sector is so developed that the policies and legislation are suited to industrial agriculture (characterized by monoculture establishments). On the other hand, the European Union legal reforms have led to the inclusion of agroforestry in agricultural policy frameworks. For example, there was a review of the Common Agricultural Policy of 2001 (in which subsidies were based on surface area). Between 2001 and 2010, beginning with intercropping systems, all agroforestry systems progressively became eligible for subsidies established by the policy, and now all agricultural lands are eligible, regardless of the degree of tree cover. This reform can be adopted by African states to promote the development and scaling-up of agroforestry (De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a; Zerihun et al. 2014).

10.3.1.1.9 Policy Constraints

National forest policies and forestry programs rarely support agroforestry in most African states. However, the most critical preconditions for the advancement of agroforestry could be an enabling policy environment that favours smallholder rural development and appropriate institutional support for agroforestry (Franzel and Scherr 2002b; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a, b; Zerihun et al. 2014). At the local level, challenges of policy and institutional frameworks include:

1. Local policies: Some local customary practices and institutions prevailing in the subregion, especially incidence of bush fires and browsing by livestock during the dry season and absence of perennial private right over land, limit the widespread uptake of some agroforestry technologies.

2. The animals destroy the trees after planting either by browsing the leaves and removing the biomass or by physically trampling over the plants.
3. Community's institutional regulations for fruit collection as well as land and tree tenure affect the individual farmer's decision to invest in establishing an indigenous fruit tree orchard.

In the case of Zambia, however, agroforestry institutions have been working in collaboration with traditional rulers, government officials, community-based organizations, NGOs and national partners to resolve these institutional bottlenecks (Ajayi and Kwesiga 2003).

10.3.1.1.10 Lack of Tree Seed Supplies

Quality seed means seed security, and seed security guarantees food security. In other words, good quality seed and germplasm, which is pure to type and free from contamination, are vital for any meaningful progress in promoting and scaling-up agroforestry systems in Africa (Marunda et al. 2019). Currently, one of the hindrances to the advancement of some agroforestry systems, technologies, practices or methods, as they are called, is the unavailability of land access to good quality tree seeds. It is well acknowledged that in mainstream agriculture, a number of establishments (government agencies and the private sector) and national programmes for quality seed multiplication and distribution exist. However, there is little or no institutional structure or national programme to produce quality seeds for agroforestry. The lack of quality tree seed of superior genotypes is a major hurdle to the expansion of agroforestry systems in Africa. Farmers may have a need and demand for tree seed, but the supply cannot match the demand, thus, halting any meaningful progress on agroforestry systems. Therefore, a reliable large-scale quality seed production, testing, supply and distribution system or programme is essential to increase the adoption and scaling-up of agroforestry technologies. Recent studies suggest that currently there are few incentives for private sector investment in this area (Franzel and Scherr 2002b; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO, 2013a, b; Zerihun et al. 2014; Marunda et al. 2019).

10.3.1.1.11 Insufficient Extension Work

The existing government extension service in Africa is relatively strong in agricultural extension and not in agroforestry extension for various reasons, including the heavy investment and support offered to the former. Large-scale agriculture has expanded both in the public and private sectors since the early 1960s as earlier highlighted. Even mainstream forestry has learnt a lot of technologies from horticulture, which is a sub-sector of agriculture. The issue of poor extension service is compounded by the fact that agroforestry, by its nature, is a knowledge-intensive practice, which means that agroforestry technologies require skilled, knowledgeable and diligent extension workers to spread the knowledge and skills to farmers. Thus, extension services remain the only avenue or strategy for scaling-up agroforestry systems. Various research reports have cited the national agriculture and forestry extension systems in African countries as major barriers to scaling-up agroforestry.

Policies and legislation support conventional agriculture, which has become business as usual (BAU) as opposed to the sustainable ecosystem management (SEM) approach promoted by agroforestry. (Franzel and Scherr 2002b; De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a, b; Zerihun et al. 2014).

10.3.1.1.12 Lack of Skill, Knowledge and Awareness

Rigorous and continuous training and retooling are important, since modern agroforestry technologies are relatively new and emerging compared with the orthodox agricultural systems. For example, unlike field crops and horticultural crops, the conventional soil fertility management options and agroforestry trees (e.g. fertilizer trees) need skills and specialized knowledge in an integrated setting. Capacity building must be undertaken at the national level through national programmes exactly like in agriculture. In agroforestry, the initial costs of information dissemination may be high, but decrease over time, and they are critical to help farmers get started with the practice (De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a, b; Zerihun et al. 2014). Awareness raising about agroforestry has not been adequately undertaken or communicated to stakeholders, yet agroforestry technologies bring the most sustainable land management option, which directly align with the sustainable development and livelihoods (De Baets et al. 2007; Kelso and Jacobson 2011; Merson et al. 2011; FAO 2013a, b; Zerihun et al. 2014).

10.3.1.1.13 Farm and Farmer Characteristics

Gender, age, education level attained, membership to clubs, location, income from livestock sales, marital status, non-farm income, main occupation, number of years of cropping (used a proxy for farming experience), size of garden owned (in case of biomass transfer), perception of status of soil fertility, method of cultivation, previous land use of plots, length of tenure and status of land ownership (FAO 2013a, b; Dlamini 2016).

10.3.2 Opportunities

10.3.2.1 Drivers of Agroforestry Development from a Strategy and Policy Perspective

Notwithstanding the challenges faced by the agroforestry sub-sector in Africa, there are opportunities that can offer a route to the development and scaling-up of agroforestry systems. The key drivers of agroforestry development would include the following according to FAO (Food and Agriculture Organization of the United Nations) (2013a):

1. Contextual drivers: Prevailing conditions and institutions determine the trends in agroforestry development. For example, high population density, land shortage,

lack of arable land, urbanization, deforestation, soaring input prices and lack of defined boundaries (planting trees on boundaries becomes an option for farmers).
2. Internal capacities: Agroforestry development is also driven by leading actors and early adopters who can promote agroforestry systems; when small- and medium-size producers have guaranteed access to land and to tree product markets, they can actively engage in agroforestry.
3. Policy as a driver: The role of policies as drivers is mainly to create a favourable economic and institutional environment in which private local actions can be carried out without significant restrictions.

10.3.2.2 Scaling-up of Agroforestry Technologies

Agroforestry has unquestionable value to both agriculture development and environmental protection, and, hence, scaling-up agroforestry is the best option in the sustainable development dispensation.

Better than the above drivers of agroforestry development, there are several strategies for enabling the scaling-up of these technologies. According to Ajayi et al. (2006), to realize the full value or impact of agroforestry, three key issues ought to be considered.

1. First, fine-scale variation in social, economic and ecological context and how this creates a need for local adaptation.
2. Second, the importance of developing appropriate service delivery mechanisms, markets, institutional contexts and technologies.
3. Third, appropriate research design, within the scaling process, that enables co-learning among research, development and private sector actors.

This requires a new paradigm shift that builds on the previous integrated systems approaches but goes further, by embedding research centrally within development praxis (Ajayi et al. 2006).

Considering the intricacies of factors that affect scaling-up, going to scale requires vertical and horizontal processes (Ajayi et al. 2006). The vertical process embodies efforts that influence policymakers and development partners and is generally institutional in nature. The horizontal process (also referred to as scaling-out) refers to the spread across communities and institutions and geographic boundaries.

Mutually re-enforcing processes illustrate scaling-up agroforestry technologies. Agroforestry partners (implementing partners and agencies as well as programme/project executants) have concentrated efforts on a process of institutionalizing agroforestry in the research, extension and development and education arenas in order to get policymakers, researchers, extension workers, development workers, educationalists and farmers to forge their efforts jointly to address the factors that influence going to scale (Ajayi et al. 2006).

10.4 Advancing Agroforestry on the Policy Agenda

10.4.1 The Need to Promote and Regulate Agroforestry Through Policies

FAO (2013a) gives factors and issues justifying and motivating why agroforestry should be promoted and regulated through policy and strategy considering the lack of buy-in and support compared to conventional agriculture.

1. Eliminate legal and institutional constraints on agroforestry: In cases where science-based models are available like in agroforestry technologies and practices – those solutions should not be impeded by regulatory constraints or prohibitions.
2. Support positive outcomes of agroforestry: Government has to appreciate the multiple ecosystem functions and ecosystem services provided by agroforestry and support these technologies through national policies and legislation. The valuation of agroforestry benefits should be infused into the System of National Accounts.
3. Compensate farmers for the delay in returns: The main goal of the policies would be to reduce risk while increasing returns on smallholder investment in trees. There are several priority areas in which policy support is urgently needed, including institutional reform, land tenure security as well as access to resources (information, genetic and financial), markets and incentives.

10.4.2 Lessons from Success Stories

African stands to learn from success stories from within the continent and beyond in order to effectively and efficiently plan for agroforestry systems development, which could ensure survival essentials and conditions for success.

10.4.2.1 Beneficial Agroforestry to Farmers

Agroforestry systems prove successful and sustainable only when they have direct benefits for farmers. In most situations, farmers may not be willing to wait out a lengthy investment phase before realizing revenues (FAO 2013a). Policies should aim to create a beneficial context for farmers introducing trees.

10.4.2.2 Security of Tenure Rights

A clear guarantee of tenure rights can support a farmer's strategy to invest in trees on farms, including in cropland. There are few agroforestry success stories in an uncertain land tenure context (FAO 2013b).

10.4.2.3 Agroforestry Linking Sectors

For the development of agroforestry, coordination and collaboration among high-ranking decision-makers in various sectors is imperative, especially the departments of agricultural, environment and forestry. This connection between various public services may help where specific measures are elaborated to support the process (FAO 2013a).

10.4.2.4 Strict Enforcing of Forest Management Rules

Across all tropical regions, there are many countries, which have highly restricted the cutting and management of a range of species valued by farmers, requiring costly permits. Mechanisms are needed to exempt trees planted in agricultural landscapes from such regulations. On the other hand, an appropriate regulation of harvesting and effective penalties for illegal activities in natural forests could be an excellent motivation to integrate trees with farms (FAO 2013a).

10.5 Recommendations for Future Action

Based on review and synthesis of numerous case studies on the status and potential of agroforestry systems in Africa and beyond, the subsequent section provides specific recommendations concerning the design of suitable agroforestry systems/ programmes in Africa. Most of the recommendations are inspired by the work of Cook and Grut (1989).

10.5.1 Economic Analysis

10.5.1.1 Demand-Driven Agroforestry Projects

Market-led community commercialization should determine which national agroforestry systems, programmes and projects should be considered for investment. A shift from the current "business as usual" to a more innovative business approach is desired.

10.5.1.2 Return on Investment in Terms of Social and Financial Profits

Agroforestry, being the most sustainable land management option than conventional agriculture, should be supported by governments and other stakeholders based on the social/cultural, ecological/environmental (multiple ecosystem services) and economic/financial benefits that the practice provides in the long term when practiced at full scale.

10.5.1.3 Economic Policy Analysis of Factors Impacting on Agroforestry

Economic policy analysis studies on topics, such as rural financial markets, land and tree tenure systems, pricing and tariff structures as well as incentives and subsidies, which should be conducted in a quest to enable the development of agroforestry systems.

10.5.2 Institutional Support

10.5.2.1 Three Levels of Agroforestry Interventions

Institutional issues need to be addressed at three levels.

1. *Micro-level interventions*: Such as fruit trees or alley cropping, should emphasize short-term benefits, relative ease of management and project implementation at the individual or farm level.
2. *Middle-level interventions*: Such as community nurseries or woodlots, may emphasize short- or long-term benefits. Such projects should involve implementation by groups or associations. They are likely to require more specialized and intensive management and to combine economic returns to the group with social service and/or environmental benefits to the community as a whole.
3. *Macro-level interventions*: Such as windbreaks or forest plantations, emphasize long-term benefits and may be most appropriately implemented through the public sector. These projects are likely to involve the most specialized and intensive management requirements. Social and environmental benefits will be important in such projects, although economic returns may also be sought, especially where cost recovery is a goal.

10.5.2.2 Institutional Strengthening, Knowledge Management and Capacity Building

Local-level or community-based organizations and traditional structures need to be strengthened on agroforestry technologies and their complexities. Tailored training and capacity building must be delivered to social groups and local-level organizations. Further, appropriate knowledge management platforms should be created and established for information sharing and communication.

10.5.2.3 Review and Assessment of Institutional Capacity for Delivering Agroforestry Interventions

The assessment of institutional capacity needs to be carried out at the three levels described above, i.e. macro-, middle- and micro-level institutions. The selection of institutions for project implementation should be based on their strengths and competencies as well as relevance to the project themes, goals and objectives. Strengthening of existing institutions should be prioritized.

10.5.2.4 Provision for Continuous Monitoring and Evaluation and Redesign

Agroforestry programmes and projects should adopt and implement a results-based management approach so as to ensure continuous monitoring and evaluation and reporting. Midterm reviews and redesigns should be undertaken accordingly. Stakeholder participation is key at all stages of implementation of the projects or programmes.

10.5.2.5 Continuous Training, Trans- and Interdisciplinary Retooling and Strengthening Local Institutions

Agroforestry training activities should be directed to:

1. Developing holistic interdisciplinary training courses and materials.
2. Strengthening in-country institutions, both public and private.

These institutions may include government extension officers in government departments, schools, local NGOs and religious associations.

10.5.2.6 Training Needs Assessment and Tailored Training Modules: Linking Theories and Applications

Training modules, courses and workshops should be developed in conjunction with the local training institutions. Training must design to cater for grassroots as well as technical and professional cadres alike. Refresher courses for retooling agroforestry practitioners are desirable. Agroforestry stakeholders should be trained in other disciplines that are relevant to agroforestry technologies, such as financial management, human resources management, employee wellness and policy.

10.5.3 Research Priorities

10.5.3.1 Diagnosis and Design Procedure (Model of Farming Systems Research)

This agroforestry research paradigm involves four kinds of research activities:

1. Diagnostic research: including household- and community-level baseline data gathering and exploration as a foundation for identifying hurdles to performance interrogating farmer needs and priorities and ascertaining the alternative options.
2. Applied research: intended to advance a variety of agroforestry technologies.
3. Adaptive research, in which other technologies are appraised based on their location-specific appropriateness.
4. On-farm adaptive research, for examination of adoption and non-adoption of technologies. This type of research embraces both on farm adaptive and applied research.

10.5.3.2 Farming Systems Approach

Research has to be relevant and precise through concentrating on location-specific studies involving local stakeholders, with the aim of developing or formulating local solutions to solve local challenges. It should be broad and be conducted at the science/policy interface and aiming at putting policy to practice. It should also begin with a problem tree, where social, cultural, ecological, environmental, economic, financial, political and technological issues are considered.

10.5.3.3 Linking Programme/Project Monitoring to National Research and Evaluation Plan

A robust short-, mid- and long-term programme and/or project monitoring and evaluation plan, linking complex agroforestry technologies as well as national research and development plans, must be developed as top priority. An indicator tracking table for programmes and project within and between several agroecological zones would be very useful.

10.5.4 Policy Issues

10.5.4.1 Development of National Action Programmes or Strategies for Agroforestry

Governments have the obligation to lead the development and guide and monitor the implementation of innovative national policies, strategies and action plans for agroforestry systems. Multi-stakeholder participation will be cardinal. The national strategies must, at least, include a situational analysis (sector overview); a policy and legislative framework; guiding principles and core values; analyses of **s**trengths, **w**eaknesses, **o**pportunities and **t**hreats (SWOT); analyses of **p**olitical, **e**conomic, **s**ocial, **t**echnological, **e**nvironmental and **l**egal (PESTLE); and a clear vision, mission, transformational mission, strategic framework, stakeholder analysis, risk management matrix, goals, objectives and priority actions as well as budget, ending with a comprehensive monitoring and evaluation framework.

10.5.4.2 Applied Policy Research to Support Agroforestry Programmes

It is critically important to always ensure that research studies, focusing on policy issues surrounding agroforestry systems and linking them to farmers and implementing agency/implementing partner/executing agency, are carried out to inform the national policy direction. National policies should be evidence-based and research agenda should be policy driven.

10.5.4.3 Public Awareness and Education on Agroforestry Principles

Development partners have a responsibility to invest in awareness raising and education on agroforestry systems and options. Tailored education programmes should be designed and intended for policymakers, planners, extension workers, traditional leaders and grassroots about the actual and potential role of agroforestry systems to local, national, regional and international development. In addition, the educational programmes should outline the multiple ecosystem functions and services provided by agroforestry and relate these to long-term benefits of agroforestry technologies to sustainable development and transformational livelihoods.

10.6 Conclusions

Based on the foregoing review, the following conclusions are presented to enhance the development of both traditional and modern agroforestry systems and technologies in Africa.

10.6.1 Transition

Transition from traditional to modern farming systems is imperative. Research indicates that agroforestry is widespread through Africa, since the concept of combining trees and shrubs with field crops and/or livestock on one piece of land is central to many traditional farming systems on the continent. Unsustainable development has led to diminishing natural resources, including land degradation and water scarcity. Therefore, traditional and cultural livelihood strategies are no longer sustainable. For example, rapid and alarming population growth, as it relates to the sustainable livelihoods needs, has rendered such traditional systems unsustainable and ineffective. As a result, African farmers need to adopt an integrated approach to farming and develop and implement new, innovative and more effective farming systems to maximize productivity and production while ensuring environmental protection. Modern agroforestry systems have become among the key interventions of the modern times in the arid and semi-arid regions of Africa.

10.6.2 Integration

There is a pressing need to shift from sectoral to multisectoral and/or inter-sectoral approach to farming (integrated farming). In Africa, the interface between forestry and agriculture is now inevitable, and agroforestry is the option. Both agriculture and forestry have significant roles to fulfil sustainable livelihoods, in particular, food and nutrition security as well as environmental sustainability. Thus, an integrated farming system comprises agroforestry more than the orthodox agriculture or forestry practices. Development and promotion of agroforestry systems require a joint effort and collaboration between forestry and agriculture extension. Subject matter specialist should work cooperatively for success.

10.6.3 Enterprise Development

A great potential for small-scale forest enterprise development (agroforestry) exists in Africa. Recent studies indicate that, in general terms, natural forests and woodlands in Africa have been degraded to the extent that the demand for wood and non-wood forest products can no longer be met from the remaining natural forest resources. The substantial demand for wood and non-wood forest products comes from agricultural, peri-urban and urban areas. Forest products that are in high demand include fuelwood and charcoal, which can be produced through appropriate agroforestry systems by smallholder farmers and even households.

10.6.4 Governance

An effective forest governance and robust strategies are needed to promote tree planting in Africa. As long as unsustainable harvesting and utilization of forest resources are left unabated, the supply of relatively cheap fuelwood and charcoal will continue. Therefore, agroforestry may not be widely adopted for supplying fuelwood in the short- and midterm periods until economic sustainability is overtaken by ecological sustainability in the long term, i.e. when the natural stock has disappeared such that market demands cannot be met any further. When the demand for forest products exceeds the supply by huge margins, then the prices will be escalated. This implies that although agroforestry has shown massive potential to address fuelwood and charcoal needs, it cannot be expected to solve the fuelwood crisis in Africa. However, there is a strong justification to assume that the present pattern clearing of natural forests for other land uses and the prevailing unsustainable utilization of forest resources can be halted and, eventually, reversed through good forest law enforcement, governance and trade as well as promotion of sustainable forest management, including the promotion of appropriate or suitable agroforestry systems.

10.6.5 Mainstreaming

Incorporation of agroforestry/forestry activities in national agricultural policies and extension programmes will bring about the desired success. Most or all national agricultural policies and extension services/programmes in Africa should infuse elements of agroforestry and/or community forestry based on the needs of the communities (households) and adaptability of tree/shrub species to various ecological regions. The national programmes, action plans and national, regional and local projects should contain a tree planting component, providing extension services and seeds or seedlings where needed. Research should form an integral part of the projects to ensure that social/cultural, economic/financial and ecological/environmental considerations are at the heart of the agriculture extension programme.

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Part III

Tropical Agroforestry: Humid and Subhumid Regions

Agroforestry Options for Degraded Landscapes in Southeast Asia

11

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Abstract

In Southeast Asia, 8.5% of the global human population lives on 3.0% of the land area. With 7.9% of the global agricultural land base, the region has 14.7% and 28.9% of such land with at least 10% and 30% tree cover, respectively, and is the worlds' primary home of 'agroforests'. Landscapes in the region include the full range of 'forest transition stages', as identified in global analysis. A long tradition

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of top-down national reforestation and tree planting programs has not had success proportional to the efforts and resources allocated. By contrast, farmers in the region have a long tradition of retaining (and managing natural regeneration of) useful trees among planted trees (e.g. tree crops or timber) and annual crops to prevent degradation and avoiding the labour costs of weed control. Meanwhile, state-controlled forests have lost a lot of their diverse tree cover, both legally and illegally. The restoration agenda includes four levels of intensity and stakeholder involvement: (RI) ecological intensification within a land use system; (RII) recovery/regeneration, within a local socioecological system; (RIII) reparation/recuperation, within rules and rewards set by the national policy context; and (RIV) remediation, requiring international support and investment. 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. The chapter summarizes lessons learnt in 26 landscapes, grouped in seven 'degradation syndromes': Degraded hillslopes, fire-climax grasslands, over-intensified monocropping, forest classification conflicts, drained peatlands, converted mangroves and disturbed soil profiles. It also addresses two overarching concerns: disturbed hydrology and supply sheds at risk. In each landscape, a driver-pressure-state-impact-response analysis of the socioecological system supported a diagnosis beyond the primary degradation symptoms. Appropriate actions reflect six requirements for effective restoration: (1) community involvement, aligned with values and concerns, (2) rights, (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 (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 our 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.

Keywords

Agroforest · Community-based forest management · Forest transition · Rights-based approach · Sustainable development goals

11.1 Introduction

Land degradation is a pervasive, systemic phenomenon that occurs in all parts of the terrestrial world and can take many forms (IPBES 2018). In Southeast Asia, like elsewhere, farmers have long understood that investing in avoiding land degradation and in the restoration of degraded land makes sound social and economic sense, and

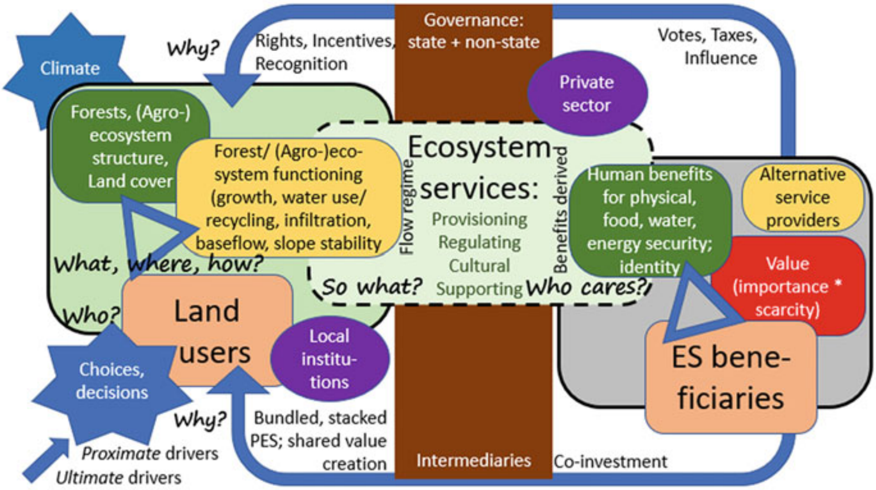

Fig. 11.1 *Cascade of (agro)ecosystem structure to function and functionality* ('ecosystem services', ES) from a human perspective that relates 'degradation' and 'restoration' concepts that generally involve ES beneficiaries beyond the direct land users, which they need to influence; proximate drivers shape decisions by land users within the landscape; ultimate drivers influence land use decisions and who uses land for what (Namirembe et al. 2017)

they have invested in trees as part of their landscapes and farming systems. In doing so, they connect the three scales at which agroforestry is relevant: plot level, multifunctional landscapes and the interface of agricultural and forestry policies (van Noordwijk et al. 2019a). In this chapter, we will discuss examples of these three scales, within a 'systems' framing of degradation and restoration as related processes and relating restoration options to the specificities of context and purpose. The aim of restoration, as interpreted here, is to create the agroecological conditions in which sustainable intensification is ecologically, socially and economically feasible, enhancing functionality. Agroecology is defined by its goals and approach, rather than by a specific choice of method (HLPE 2019), but agroforestry can be an important component of locally adapted land use systems. Degradation and restoration involve concepts of (agro)ecosystem structure (e.g. vegetation, soils), function (e.g. nutrient, carbon and water cycles), land users (gearing structure and function towards their interests), ecosystem services (ES) and ES beneficiaries and ways they can influence land users (Fig. 11.1).

What is now understood as agroforestry has emerged in many forms across Southeast Asia (de Foresta et al. 2000; van Noordwijk et al. 2019d). It can, now that policy recognition across the usually segregated agricultural-forestry continuum has been confirmed in high-level policy documents of the ASEAN network of Southeast Asian nations (Catacutan et al. 2019), be an important part of the solution for achieving Sustainable Development Goals in a densely populated region (147 km^{-2}) with 8.5% of the human population (663 M in 2019) living on 3.0% of the global land area and an average tree cover on agricultural lands of 33% (Zomer

Fig. 11.2 *Multiscale perspective on restoration efforts* (top-down with a focus on rights or bottom-up starting from incentives) and on the five aspects (rights, land use practices, markets, local and global ecosystem services) that along with intrinsic and social motivation need to synergize

et al. 2019). With 7.9% of the global agricultural land base, the region has 14.7% and 28.9% of such land with at least 10% and 30% tree cover, respectively (van Noordwijk et al. 2019d). As elsewhere, tree cover on agricultural lands is positively related to rainfall in Southeast Asia (van Noordwijk et al. 2019d). Degradation-to-restoration shifts operate in a complex multi-stakeholder environment and need to be understood as processes in socioecological systems, nested within broader policy feedback loops (Fig. 11.2).

Land use options such as agroforestry and their constraints as solutions for degraded landscapes in Southeast Asia can be interpreted in a driver-pressure-state-impact-response (DPSIR) framework (Kristensen 2004). Restoration actions need first to address and deflect higher-level drivers (**D**) of degradation; otherwise, progress at specific locations leads to negative 'leakage' effects elsewhere. They then need to disentangle the social and ecological pressures (**P**) to which specific landscapes respond, in response to the drivers. A typology of degradation cause-and-effect relations and their intensity and feedback loops is needed to go beyond system state (**S**) metrics of areal extent (X million ha) and get sufficient clarity on the ecological and social impacts of degradation (**I**) that stakeholder coalitions for change can emerge that want to co-invest in a response (**R**) to restore landscape multifunctionality, at driver, pressure and system level. Restoration will have to be prepared for ongoing trends and will have implicit relevance for (or explicit reference to) climate change adaptation. Although restoration efforts will often require financial support that requires relevance for specific (siloed) objectives (van Noordwijk 2018), it will have the best chance of lasting success if it enhances the synergy between all 17 Sustainable Development Goals (SDGs) and links a rights agenda to land use practices (and the knowledge supporting it), markets and local and global ecosystem services (Fig. 11.2).

Box 11.1 Definitions
For this chapter, we define the following:

- *Degradation:* Loss of functionality of, for example, land or forests, usually from a specific human perspective, based on change in land cover with consequences for (at least one category of) ecosystem services
- *Degraded lands*: Lands that have lost functionality beyond what can be recovered autonomously by existing land use practices in a defined, policy-relevant time frame
- *Restoration:* Efforts to halt ongoing and reverse past degradation, by aiming for increased functionality (not necessarily recovering past system states)
- *Syndrome:* A set of concurrent diagnostical indicators, not necessarily linked to a common cause or driver

Within the definitions of degradation and restoration (Box 11.1), we recognize four levels of intensity of 'restoration' efforts:

- RI. Ecological intensification within a land use system
- RII. Recovery/regeneration, within a local socioecological system
- RIII. Reparation/recuperation, within a national policy context
- RIV. Remediation, requiring international support and investment

These four levels relate to a nesting (Fig. 11.3) of farming (land use) within landscapes as local social-political systems, within national entities, within an interconnected global system of common but differentiated responsibility for staying within 'planetary boundaries' (van Noordwijk and Catacutan 2017; van Noordwijk

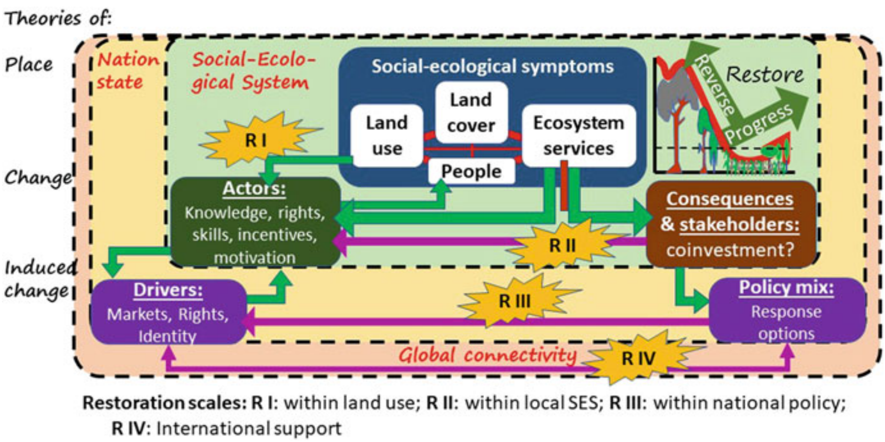

Fig. 11.3 *Nested scales of socioecological-policy systems* in relation to the four intensities of restoration discussed in this chapter

et al. 2018). While stopping the early-stage drivers of a forest transition and triggering a reversal by natural regeneration is possible in some contexts, in many others, restoration must speed up the progression towards functional tree cover that might occur at a slower pace without intervention (van Noordwijk and Villamor 2014; Dewi et al. 2017). The counterfactuals for judging the impact of specific interventions will rarely be constant: business as usual will either involve continued degradation or slow steps towards the recovery of functions.

National programs for reforestation have been tried in many different forms in the various countries of SE Asia but with limited success, relative to the efforts and budgets allocated. More than a decade ago, the rapid spread of degraded but partially recovering, secondary forest was analysed for SE Asia (Chokkalingam and de Jong 2001), with specific attention to the ‘agroforest’ part hidden within national statistics (De Jong et al. 2001). Agroforestry became recognized as an essential part of a more effective reforestation paradigm for the region (Roshetko et al. 2008b). When, however, global funding support for an increase of tree cover became available within the Kyoto protocol, confusion about forest definitions and eligibility of state forest lands proved to be a major bottleneck (van Noordwijk et al. 2008). Regardless of global funding, Southeast Asia has a rich experience in both degradation and restoration, with its diversity in biophysical settings (mainland and insular), high biodiversity (interface to two biogeographical domains), human cultural, linguistic and historical diversity, early participation in continent-wide and global trade and exchange, high current population density and resource pressure, linked to rapid progress on the achievement of national development goals. Based on methods described elsewhere (Dewi et al. 2017), a classification of Southeast Asian watersheds in six stages of ‘forest transition’ involved various quantitative aspects of tree cover and human population density (Fig.11.4).

Land cover is directly observable with current remote sensing tools, but the loss of tree cover as a symptom does not necessarily imply land degradation beyond the resilience of vegetation to return to its main functions and eventually form and structure. At the ‘gap’ level, a temporary loss of cover is indeed part of the normal successional cycles of forests—but there are questions of spatial and temporal scale: over what distance can effective seed dispersal complement any location-specific survival in seed banks, and over what time period can plant structures survive for vegetative recovery from stumps or roots, and as seeds in a seed bank? Many authors have described that traditional ‘shifting cultivation’ or ‘swidden/fallow’ rotation systems did maintain options for the swift recovery of desirable woody vegetation, while crossing some poorly quantified threshold of cropping intensity leads to fire cycles in grass-based vegetation that can arrest natural succession for many years (Cairns 2007, 2015; Xu et al. 2009). In fact, the shift towards actively assisted woody vegetation in agroforestry-based fallow has effectively dealt with the threshold in many parts of Southeast Asia, operating in environments of 10–100 and 100–1000 tree species in (agro)forests, rather than the 1–10 that are common in drier parts of the world (van Noordwijk et al. 2019b). Reliance on natural regeneration, rather than a focus on tree planting, has been advocated as a tool for large-scale forest restoration in the tropics (Chazdon and Guariguata 2016) but depends on

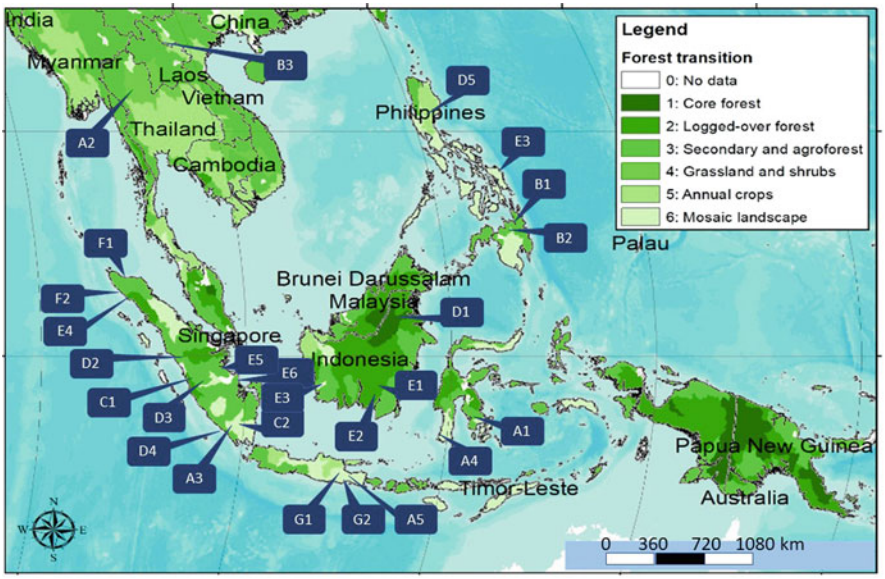

Fig. 11.4 *Map of SE Asia with forest transition stage classification* at subwatershed level (Dewi et al. 2017) with a set of specific landscapes A1–G2) that is listed in Table 11.1 and discussed in this chapter

ecological as well as social context. Brazil's current law for the protection of native vegetation (known as the 'New Forest Law') allows for ecological restoration through agroforestry systems, as long as they maintain or improve the area's basic ecological functions (Miccolis et al. 2016, 2019)—as far as we know there is no comparable statement in any of the Asian laws, although the ecological practice would certainly justify this type of legal recognition.

Beyond the regeneration capacity of diverse woody vegetation and its consequences for restoration (Wills et al. 2017), degradation can also affect soil conditions, with soil organic matter as an indicator of many chemical, physical and biological aspects of soil health. In swidden-fallow cycles, it is common for breakdown of soil organic matter (conventionally measured in the C_{org} concentration) to provide part of the nutrient basis of crop production, with subsequent recovery on fallows. Crossing a critical swidden-fallow time ratio, however, can induce a downward trend of C_{org} and lead to a 'degraded soil', that will have lower soil fertility and crop production, further limiting the inputs of roots and crop residue to the soil. Interventions that support biological nitrogen fixation (by the inclusion of woody or herbaceous leguminous plants) or use of industrial fertilizer can break the negative trend and lead to recovery (Box 11.2). The roles of agroforestry in this type of recovery have been extensively studied and reviewed (van Noordwijk et al. 2019c).

Examples of success (and failure) of agroforestry-based land restoration in Southeast Asia for the rest of this chapter will be drawn from seven settings:

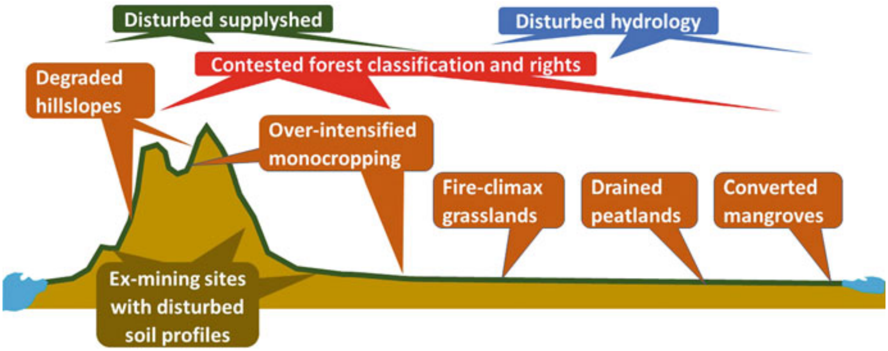

Fig. 11.5 *Approximate positions in the landscape* (such as a schematic cross-section of Sumatra island) of seven degradation syndromes and associated restoration cases and two overarching concerns discussed in this chapter

(A) degraded hillslopes, (B) fire-climax *Imperata* grasslands, (C) mangroves (and associated acid sulphate soils), (D) drained peatlands, (E) mining practices, (F) over-intensified monocultures and (G) disturbed hydrology (Fig. 11.5).

Box 11.2 Soil Carbon Transition Curves in Relation to Land Use Intensification

In the third quarter of the twentieth century, a remarkable shift occurred in upland Southeast Asian soils where a long period of soil degradation and declining soil organic C (C_{org}) concentrations was reversed into an upward trend (Minasny et al. 2012). Beyond the phenomenon of 'soil carbon transitions' as such, the interpretation of underlying drivers and causes is debated in the literature (van Noordwijk et al. 2015; Minasny et al. 2017). The pattern is consistent with a reasonable set of simplifying assumptions but also sensitive in its details to several parameters.

If fallow periods that rebuild soil organic matter are sufficiently long relative to the cropping period ('shifting cultivation' or 'long fallow'), sustainable grain production is feasible at acceptable returns to labour (Fig. 11.6). Higher grain yields per unit land can be achieved, along with degrading soils and declining yields per unit labour, by shortening the fallow periods—but this is an unsustainable degradation scenario. A shift to increased nitrogen input, through active biological N_2 fixation and/or industrial fertilizer, is needed to reverse the degradation, with effects on 'grain yield per unit labour' (including the labour needed to earn the costs of fertilizer inputs) depending on fertilizer costs. Depending on how far degradation had proceeded after the first intensification ('no more fallows') before the second phase of intensification starts, it will take time to rebuild the soil organic matter pool with increased crop root inputs, but recovery is possible. Economic and climate mitigation

(continued)

Box 11.2 (continued)
(greenhouse-gas emission) effects per unit land and per unit labour accompany this C-transition, with details depending on local socioecological context, reflected in a range of parameters for the simple model presented here. The 'Simple Crop Corg' model was set up to generate soil carbon transition curves that are consistent with simple assumptions about soil carbon dynamics during fallow and cropping stages. The model provides estimates of yield, organic matter dynamics, yield per unit labour and net GHG emissions per unit yield and is available at https://doi.org/10.34725/DVN/WDVCU5. The results in terms of grain yield per day of work and thus farm-level attractiveness of the second intensification transition point depend on both fertilizer prices relative to labour costs and several technical efficiency coefficients that are specified in the model. Rather than claiming to be representative of the full range of conditions, the model shows that soil C recovery based on crop root residues is in the range of possibilities.

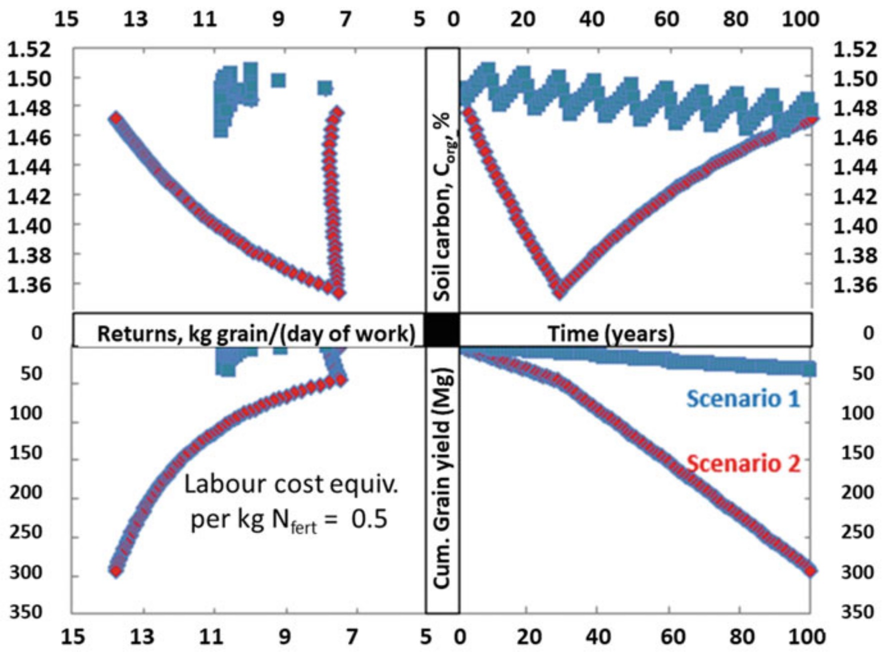

Fig. 11.6 Four-quadrant representation of the output of the Simple Crop Corg model for two scenarios (continued fallow-crop rotations) and permanent cropping first without and then with specific N inputs from fertilizer or N2-fixing crops

Across the seven examples of restoration in SE Asia, we find relevance for four 'modalities' of restoration: (1) leave alone, (2) assisted regeneration, (3) planting/ growing of trees and (4) soil and water management (Table 11.1).

11.2 Contextualizing Degradation and Restoration

11.2.1 Local Community Initiative as Starting Point

At the centre of Fig. 11.2, local institutions are depicted as the linchpin of restoration. A main reason for degradation is, strange enough, the human coping capacity. The gradual loss of functionality can be compensated by increasing efforts to obtain the resources and services needed elsewhere. Dealing with symptoms by adaptation, rather than with underlying causes, allows the environment to further slide away from a desirable state. Triggers for actions that no longer accept *status quo* have in many of the landscapes we know been 'disasters', events that exceeded the local coping.[1] Behind many of the ES-supportive agroforestry landscapes are stories of landslides, floods, fire and haze episodes or other disasters that gave a platform to the local voices who strive for change.

Change will only happen and be sustained if it has local support, often in the form of collective action and co-investment of time, land, skills, social capital and (often more limited) financial resources. Awareness that ongoing degradation is a risk, even before disasters observed elsewhere are locally replicated, can be supported by external contacts (television, social media) but more often by local people who temporarily lived or visited elsewhere and can share their experience and expectations.

A similar process of adaptation preventing a challenge to underlying drivers may well be at the heart of accepting existing inequalities, including a gender imbalance in rights, respect, responsibilities and rewards. As gender equality is a central part of the post-2015 sustainable development agenda, it deserves attention in all parts of the DPSIR analysis (Villamor et al. 2014a). Differences in opportunities, challenges, preferences and responses between men and women are important in the relationship between poverty, climate change and land degradation (Kabeer 2005; Meinzen-Dick et al. 2014; Catacutan et al. 2015). In designing land restoration options, the links between gendered land use choices (i.e. preferences of new land use options) and their implications to ecosystem services provision need specific attention (Catacutan and Villamor 2016). Often, men and women have contrasting views and choices regarding land, which could influence future land uses and management practices (Villamor and van Noordwijk 2016). Coalitions for the restoration of environmental functionality are more effective when women and young people of all genders are involved, beyond existing gender and age hierarchies in formal decision-making.

[1] For an example, see https://agroforestri.ub.ac.id/2017/10/23/vlog-1-petani-agroforestri-di-ngantang-malang-manajemen-af-dan-kesuburan-tanah/

Table 11.1 Degradation syndromes and studied restoration efforts through agroforestry with examples in Southeast Asia contextualized in the 'forest transition' stage of the surrounding subwatershed

Degradation syndromes, example landscapes	Forest transition stage	Rights, recognition, co-management[a]	Restoration modalities[b]	ES co-investment[c]	References
A. Degraded hillslopes					
1. Kendari, SE Sulawesi	3	Stable	2,3		Wartenberg et al. (2019)
2. N Thailand	3(4)	Stable	1,2		Box 11.3
3. Sumberjaya, Lampung	6	HKM	2,3		van Noordwijk et al. (2019i)
4. S Sulawesi	6	Stable	3,4		Mulyoutami et al. (2015)
5. Rejoso, E Java	6	Stable	3,4	New	Leimona et al. (2019)
B. Over-intensified monocropping					
1. Claveria, Philippines	3	Ex land reform	3,4		Mercado et al. (2005)
2. Lantapan, Philippines	4(6)	Stable	3,4		Catacutan and Mercado (2003)
3. NW Vietnam	5	Stable	3,4		Box 11.4
C. Fire-climax grasslands					
1. Lake Singkarak, W Sumatra	3	Stable	2,3	RUPES	Burgers and Farida, (2017)
2. North Lampung	6	Stable	3		Purnomosidhi et al. (2005)
D. Forest classification conflicts					
1. Setulang, N. Kalimantan	2	Partly contested	1,2	Failed1	Wunder et al. (2008)
2. Batang Toru, N Sumatra	3	Partly contested	1,2		Martini et al. (2012)
3. Lubuk Beringin, Jambi	3	Hutan desa	2,3	RUPES	Akiefnawati et al. (2010); Villamor et al. (2014b); Dewi et al. (2013)
4. Krui, W. Lampung	3	KDTI	2,3	RUPES	Kusters et al. (2007)
5. Kalahan, Philippines	4	Indigenous claim	2,3		Leimona et al. (2009)
E. Drained peatlands					
1. Ex-Mill-ha-rice, C Kalimantan	2	Contested	3	Failed2	Galudra et al. (2011)

(continued)

Table 11.1 (continued)

Degradation syndromes, example landscapes	Forest transition stage	Rights, recognition, co-management[a]	Restoration modalities[b]	ES co-investment[c]	References
2. Pulang Pisau, C Kalimantan	2	Several Hutan desa	2,3,4	BRG	Suwarno et al. (2018) Tata and Tampubolon (2016)
3. Lamandau, C Kalimantan	3	Stable	1,2	REDD+	Janudianto et al. (2011)
4. Tripa, Aceh	3	Contested	1,2,3		Tata et al. (2014)
5. TanJaBar, Jambi	3	Partly contested	2,3,4		Galudra et al. (2014); Tata et al. (2016)
6. Musi Banyu Asin and Ogan Komering Ilir, S Sumatra	3	Partly contested	2,3,4	BRG	Box 11.5
F. Converted mangrove					
1.Pidie: Post-tsunami	3	Stable	3		Roshetko et al. (2008a)
2. Aceh Barat: Post-tsunami	3	Stable	3		Lusiana et al. (2011)
3. Post typhoon Haiyan, Philippines	6	Stable	2,3		Carlos et al. (2015)
G. Disturbed soil profiles					
1. Bangsri: Sand mining	5	Stable	3,4		Box 11.6, Hairiah (2018)
2. Kali Konto: Kelud ash	6	Stable	2,3,4		van Noordwijk et al. (2019e)

[a]Tenure regimes; HKM, community forestry agreement; Hutan desa, village forest agreement; KDTI, special forest designation

[b]Modalities; 1, Leave alone, let natural processes prevail; 2, assisted/managed natural regeneration; 3, tree planting/growing; 4, soil and water management interventions

[c]ES co-investment; RUPES, (Leimona et al. 2015); BRG, Indonesian Peat Restoration Agency; Failed1, attempts for biodiversity-based finance; Failed2, Australian C project

Environmental degradation often affects women disproportionately, with girls prevented from attending school by being tasked to fetch water from faraway wells with clean water a 'poster child' image. Benefits of restoration can thus accrue to most vulnerable groups in local societies—if only they get a voice in decisions on when, what, where and how. Reviving collective action for resetting the clock on environmental degradation can be a starting point for further challenge to existing hierarchies—one of the reasons that 'the powers that be' may be reluctant and resist transformative actions that disrupt not only ongoing degradation but also the existing hierarchies that tolerated, or even benefitted, from them.

While slowly creeping, locally driven, degradation is a common cause of loss of functionality, degradation can often be traced to externally mediated or initiated resource extraction (e.g. timber, coal, mineral deposits) or modification (e.g. roads, reservoir construction, externally managed plantations). In this context, the concept of 'free, prior and informed consent' (FPIC) may need to be broadened to assessing and adopting social safeguards for all planned programs (de Royer et al. 2013). As such interventions tend to offer short-term employment, it may 'buy votes' in local community discourses while causing uncompensated costs to others. Once awareness of such change has passed a threshold, where it starts to further grow as an issue of concern beyond the initial advocates, conflicts arise with the external agents and the government entities and officials that 'legalized' these actions through permits in exchange for (il)legal levies and fees. Depending on political context and strength of local voices (e.g. in elections), conflict resolution may be initiated, and a restoration agenda may be furthered.

It is here that the lack of formal recognition of agroforestry exacerbates problems in a policy and spatial planning framework that only recognizes 'agriculture' (usually within a fully privatized land ownership perspective) and various 'forest' categories that exclude local access and use. While forestry laws have over the past decades accommodated forms of 'community-based forest management' in many countries, the implementation is often slow and far behind on publicly stated targets. Its administrative procedures and multilayered approval remain complex (Akiefnawati et al. 2010; de Royer et al. 2018) and its basic assumptions of the constitutional legality of state forest claims (hence community-based forest management rather than community forestry) remain presumptuous in the absence of legally prescribed gazettement of state forest claims. An undifferentiated 'community' perspective is often as misaligned with collective action formats as the agricultural assumption of fully private property rights regimes. In between, new ways of identifying individual and collective rights and responsibilities remain needed. Traditional resource management, known as 'adat' in Indonesia[2] (de Royer et al. 2015), provided such middle ground but often needs updating and change to current pressures and opportunities. The current 'bundle of rights' with regard to land is

[2]As 'adat' forms the central letters of degradation, its demise can be seen as one of the causes and its reinvention as part of the solution.

currently understood (Galik and Jagger 2015; van Noordwijk and Catacutan 2017) to include the following:

- *Access*: entering a defined physical property
- *Harvest/withdrawal*: obtaining 'products' of a resource
- *Management*: regulating internal use patterns and transforming or improving the resource
- *Alteration*: changing the set of goods and services provided (and stated objective reflecting this)
- *Exclusion*: determining access rights for others
- *Alienation*: selling or leasing some or all other rights

Restoration activities commonly interact with all such rights but need to be based on an understanding that they don't necessarily coincide with a single concept of 'ownership'.

Action to modify land use, including restoration, starts with dissatisfaction with status quo, visions of alternative futures, trust in agents of change and realistic step-by-step pathways out of the current situation (Villamor et al. 2014a). Too often, extension' designs have assumed that the lack of technical know-how of the steps involved would be the limiting step. Farmer-to-farmer approaches to extension provide a more all-round answer to the requirements for change, even if in technical terms it may not be superior to expert advice as basis of extension (Martini et al. 2017). Hybrid approaches are becoming more common in 'rural development' programs and need to be embraced in 'restoration' versions of such (van Noordwijk et al. 2019h).

11.2.2 Methods for System Analysis of Restoration in a Nested Governance World

A two-way classification of 'contextualized issues' and 'adaptive solutions' can help clarify the 'what?', 'where?' and the technical side of 'how?' of restoration. It has implications for the social dimensions of 'who?', 'so what?' and 'who cares?' and the entry points to 'driver' level solutions, but these require a third, process-oriented dimension. Process-wise, success is understood to depend on effective diagnosis and ways of addressing (I) community-driven motivation and responsive polycentric governance structures, (II) rights and tenurial security, (III) means, knowledge of and skills in sustainable land management practices, (IV) markets for inputs and outputs and (V) the generation of downstream ecosystem service benefits. Together these can initiate adaptive learning cycles that create turning points (from decline to recovery) in local tree cover transition curves and create co-benefits that justify co-investment.

The purpose of the initial characterization is to allow interested outsiders, like yourself, to connect to the insider's perspective of those who live in the area, with the

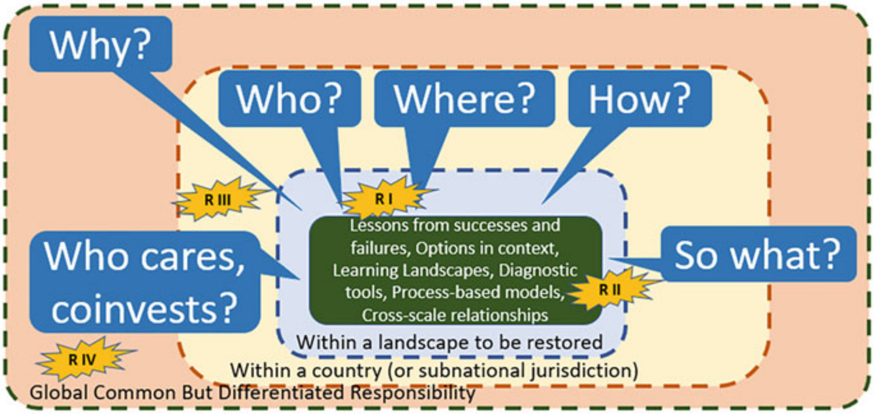

Fig. 11.7 *Six questions that drive a socioecological systems understanding* of the driver-pressure-state-impact-responses (DPSIR) loops around degradation and restoration, with agroforestry as part of a broader livelihoods and nature-based solutions agenda

expectation that a more systematic analysis can also provide new insights for those who know the place, but who may take many of its features for granted.

Six leading questions to understand landscapes as socioecological system (Minang et al. 2015) can connect an understanding of past degradation and what it takes to initiate restoration (Fig. 11.7):

Why? Assessing past degradation and its drivers
Who? Settlement history and ethnicity, tenure perspectives and gender differentiation
What? Land use practices, their productivity and resource dependency
Where? Spatial structure of landscape as land use imposed on underlying geomorphology
So what? Effects of the current situation on ecosystem functions and targets for restoration
Who cares? Identifying livelihood goals and stakeholders in restoration

A range of methods are available to find answers to the six categories of questions and support the development of 'theories of induced change' that can be used for project designs (Fig. 11.8). The negotiation support toolbox developed in Southeast Asia (van Noordwijk et al. 2013) is focussed on the divergence of three knowledge systems: local ecological knowledge, public/policy knowledge (the underpinning of policies) and science (of a full range of disciplines). The toolbox starts with three initial appraisals and then proceeds after a first reconciliation of the three knowledge systems, zooming in on aspects that may provide traction for change (Table 11.2).

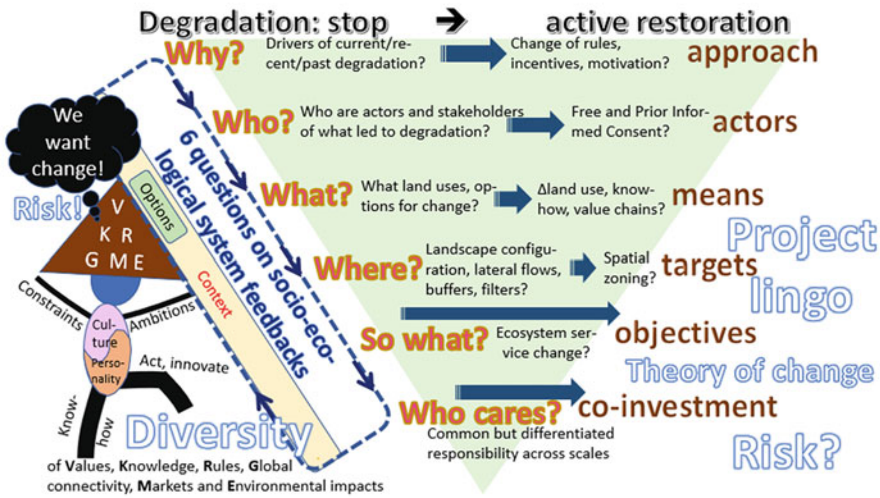

Fig. 11.8 Project design terminology related to the six primary questions for analysis of a socioecological system to understand 'options-in-context' once local actors are committed to change

Table 11.2 *Assessment steps in a negotiation support process* based on the NSS toolbox (van Noordwijk et al. 2013)

	Who	What	Where	So what	Who cares	Why
Initial appraisal	Poverty, livelihoods (PAPoLD)	Participatory landscape appraisal (PaLA)			Drivers of observed land use change (DriLUC)	
More detailed assessments of options	Livelihoods and land use: Trees, agroforestry technology and markets (10 tools, 5 models)		Ecosystem services and trade-offs (11 tools, 8 models), e.g. rapid hydrological appraisal (RHA) for hydrology		Transformations, governance, rights (8 tools) e.g. RATA for tenure claims, WNoTree for degradation diagnostic	
Synthesis	Negotiation support as a process (5 tools)					
	Planning of strategic restoration interventions in local context					

Innovative gender research methods are available to better understand gender issues in local context and identify gender-responsive solutions/approaches that foster transformational change in agriculture, forestry, health and food security, value chains, payments for ecosystem services, property rights and landscape management (van Noordwijk et al. 2013; Catacutan et al. 2014; Colfer et al. 2015; Andeltová et al. 2019).

11.3 Seven Degradation Syndromes and Restoration Actions through Agroforestry

Syndromes here refer to a set of concurrent diagnostical indicators, not necessarily linked to a common cause or driver. Just as in the medical use of the syndrome concept, further diagnostics are needed to assess appropriate courses of action.

11.3.1 Degraded Hillslopes

In land-scarce parts of Southeast Asia, farmers found ways to establish woody perennials along contours in their swiddens and by doing so reduce erosion and facilitate the rapid establishment of fallows (Fig. 11.9). The farmer-developed technology became the inspiration for a Sloping Agricultural Land Technology (SALT) that was widely promoted. Establishment of regularly pruned hedgerows on sloping land became one of the most popular forms of agroforestry in the 1980s. Farmers in the Philippines, however, modified the technology to suit their needs: they developed hedgerow establishment methods that required less labour, eliminated grasses that were too competitive with crops, stopped planting trees that were initially intended to produce green manures, and planted species that might provide direct cash returns (Fujisaka 1993). The different systems they used

Fig. 11.9 Establishment of local woody species (including *Leucaena leucocephala*) as practices in parts of Flores (Indonesia) became the inspiration if a contour hedgerow intercropping system for restoring degraded slopes, with less tree diversity than found in the area where the technology originated (Photographs: Meine van Noordwijk/World Agroforestry)

controlled soil erosion equally and effectively, although grazing of hedgerows by neighbours' cattle was a problem. Replacing nitrogen-fixing trees by a managed regeneration of grass, in naturally vegetated strips, as the start of terrace risers (Garrity 1996) reduced the need for labour-intensive pruning, but it still led to differential soil fertility or 'scouring' within the terraces formed (Agus et al. 1999). Elsewhere, the economic interest of farmers shifted from the food crops in swidden to the products that introduced (e.g. *Hevea brasiliensis*) and local (e.g. *Durio zibethinus*) trees could provide. Although there was considerable soil movement in the plot in the year of slash-and-burn land clearing, little of that reached the streams, and a fertile zone next to the stream facilitated subsequent agroforest management (Rodenburg et al. 2003). In some cases, however, external support for the establishment of desirable trees was found to be needed (Box 11.3).

Box 11.3 Supporting Indigenous Trees with Restricted Means of Dispersal in NW Thailand

In many parts of Southeast Asia, agriculture switched from swidden-fallow systems on sloping land to an agroforest pathway, where the trees and other components, such as rattan (Tata 2019a), tubers or mushroom, became more important than the annual crops in the swiddens (Cairns 2007, 2015). Elsewhere, however, the surrounding forest matrix had lost much of its diversity, and the spontaneous establishment of desirable forest species became slow and unreliable (Wangpakapattanawong et al. 2010). To deal with such situations, a forest restoration approach with 'framework' species was developed (Elliott et al. 2003), where the rapid establishment of a tree canopy was expected to attract seed dispersants and facilitate establishment of a wider array of species. As little knowledge existed of the specific nursery requirements for a wide array of desirable forest tree species, research focussed on filling these knowledge gaps.[3] Rather than by a lack of biological-technical knowledge, however, the experience of (agro)forest restoration in NW Thailand shows that the social aspects of transforming conflicts over control and ownership into a win-win opportunity for all are the most challenging step towards success (Elliott et al. 2019).

11.3.2 Fire-Climax Grasslands

In the early 1990s, *Imperata cylindrica* ('alang-alang', or 'cogon')-dominated grasslands were estimated to occupy 35 Mha in tropical Asia, roughly 4% of the total land area, with 8.5 Mha in Indonesia alone (Garrity et al. 1996). These grasslands were closely associated with annual fires that prevented the natural

[3] Further references can be found at http://www.forru.org/en/content.php?mid=203640

succession to secondary forests, and effective fire control was a key step towards ecological restoration (Wibowo et al. 1996). Where some of these grasslands were found on degraded hillslopes, with shallow and compacted soils that enhanced surface runoff and downstream flooding, others were not less fertile than the forest soils from which they had been converted had been, once the litter layer had been removed by slash-and-burn land clearing (Santoso et al. 1996). The grasslands were widely seen as an underutilized resource that could be reclaimed for more intensive food crop production or smallholder timber-based agroforestry (van Noordwijk et al. 1996; Purnomosidhi et al. 2005), deflecting pressures for further forest conversion (Garrity et al. 1996). Agroforestry-based technologies for reclamation of *Imperata* grasslands were popularized, with assisted natural regeneration (allowing tree seedlings to escape the early competition and fire risks) as a low-cost alternative to the use of herbicides (Friday 1999; Murniati 2002). A number of studies pointed to local success in replacing *Imperata* grasslands with diverse agroforests once local communities had secured rights to restore on their own terms (de Foresta and Michon 1996). A recent reconfirmation that such is indeed possible is provided by Burgers and Farida (2017) for the Lake Singkarak area in West Sumatra. As a large part of the grasslands was found to be part of 'state forest' lands, their continued existence came to be seen as a symptom of property right conflicts and market failures to allow higher-value land uses to emerge (Tomich et al. 1996). At least, part of the fires that gave rise to *Imperata* grasslands were attributed to conflict ('fire as a weapon') between local people and large-scale forest plantation concessions that occupied lands they saw as their own (Tomich et al. 1998). Subsequent analysis has shown that widespread *Imperata* grasslands were indeed transient phase in the land use history of many parts of Sumatra, even when their extent was still increasing in Kalimantan and areas further east in Indonesia (Ekadinata et al. 2010). Analysis of long-term land cover change in Southeast Sulawesi by Kelley et al. (2017) suggested that the smallholder tree crop economy likely produced both forest loss and *Imperata* grassland restoration in this region. The study by Zhang et al. (2019) in the Philippines showed that hydrological 'restoration' of deep infiltration of rainfall in reforested *Imperata* grasslands may take decades rather than years, depending on how far the grasslands had been compacted after the old tree root channels of preceding forest vegetation had been lost.

Once economically more attractive (e.g. land with logging rights and expected income) options have become closed off, the reclamation of *Imperata* (and similar) grasslands is technically feasible, both by smallholders (establishing adequate tree cover to shade out the grass, with less than 20% of solar radiation reaching the understorey according to Purnomosidhi et al. 2005) and large-scale operators (often relying more heavily on the use of glyphosate and other herbicides). Property rights, including a rationalization of forest classifications, have been a starting point for most restoration successes analysed so far.

11.3.3 Over-Intensified Monocropping

A vast extent of agricultural land in Southeast Asia is under over-intensified monoculture systems (e.g. maize, rice, sugarcane, pineapple, cassava, banana). As part of 'modernization', large areas of these systems have become mechanized, with high chemical input use and where they are practiced on upland sloping lands with inadequate soil conservation. The application of soil and water conservation technologies in monocropped sloping fields is considered labour and capital intensive, making it difficult to convince farmers to shift their practice. Consequently, every year, an enormous amount of fertile topsoil is being lost and chemical inputs are wasted—this process undermines future land productivity, causing farm yields to decline and input costs to increase. Consequently, local and national economies experience significant losses, threatening the sustainability of agricultural systems. Box 11.4 describes a case study in Viet Nam, where efforts to reintroduce agroforestry as part of restoration depend on finding tree species with good market demand and accepted/supported by the government.

Box 11.4 Promoting Agroforestry as Sustainable Agricultural Practice in Northwest Vietnam

Agroforestry options for land restoration vary considerably within Vietnam (Mulia et al. 2018). Northwest Vietnam covers an area of about 5.64 million ha and is home to ethnic minority groups. The region is mountainous with 60% of lands having slopes at or steeper than 15 degrees (Staal 2014). Many local people rely on agriculture for livelihood (Beck 2017), with shifting cultivation and maize monoculture as common agricultural practices on the fragile sloping lands (Hoang et al. 2017). The region had a poverty rate of 13.8% in 2016 compared to the national rate of 5.8% (Vietnam statistic yearbook 2017). Incidences of soil erosion and declining agricultural yield owing to soil degradation are common across the region (Hoang et al. 2017; Zimmer et al. 2018).

Hoang et al. (2017) recommended the agroforestry system, i.e. integration of trees into agricultural lands with contour planting for Northwest Vietnam. The annual crops can be combined with timber or fruit trees and strips of grass for fodder or market as an additional source of income. Roshetko et al. (2017) implied that this recommended practice is simple and low cost with proven conservation measure and has direct positive environmental and economic benefits such as more permanent soil cover, improved soil structure and infiltration, diversified agricultural products and income and higher carbon storage and soil organic matter. La et al. (2016) provide guidance for establishing the system.

According to Zimmer et al. (2018), adoption rate by farmers in the Northwest region to the recommended practices was slow due to the lack of

(continued)

Box 11.4 (continued)
knowledge and lack of financial backup during the transition from the current into new practices. Hoang et al. (2017) identified that farmers still felt uncertain on the market access to new products and had difficulty accessing credits for investment. To enhance the adoption rate, the government's supports in providing better access to market, e.g. through improved infrastructure and information network, better access to credit, more certainty in terms of land tenure by providing land use certificate and better extension system to increase knowledge and skills in plot management option, are necessary (Fig. 11.10).

Fortunately, much is now known about various ways to control soil erosion while further increasing productivity and enhancing the long-term sustainability of intensive farm production (Catacutan 2008. In Mindanao island in the Philippines, contour farming and agroforestry have proven to drastically control soil loss by retaining fertile soil and chemical inputs in the fields. These practices first involve the establishment of grass strips along contour lines, which enables farmers to produce more high-quality forage for their livestock, and second the combination of high-value tree crops (Mercado et al. 2005). This agroforestry model dramatically enhances farm income compared to open-field maize monocropping and enables farmers to create a diversified and integrated farming system that dramatically increases income and protects land resources from degradation. Such agroforestry models were widely adopted predominantly by maize farmers in Mindanao via the

Fig. 11.10 Typical agricultural sloping lands in Northwest Vietnam with low tree cover and serious soil erosion (Photo credit: World Agroforestry)

Landcare approach—a social approach to technology dissemination that capitalizes on the collective action of farmers, extension workers and researchers with support from local governments (Cramb et al. 2007). Farmer-leadersv were trained by extension workers and researchers, to produce quality germplasm, and were supported to establish nurseries, to ensure availability of seedlings for a variety of tree species that farmers incorporate into their maize fields (Catacutan and Mercado 2003). Landcare groups were formed to facilitate farmer-to-farmer learning exchanges and to reach out for financial and further technical support. Measured in terms of rate and extent of agroforestry adoption and social capital, the success of Landcare in Mindanao was quite remarkable and an inspiration for similar landscapes elsewhere.

11.3.4 Forest Classification Conflicts

When practitioners of a 'landscape approach', seeking to enhance the multifunctionality of landscapes they facilitate, were asked to rank a range of factors that currently limit progress, they identified roughly half of such factors operating at and potentially modifiable within the landscape, and about half that originate at higher levels of governance (Langston et al. 2019). Among the latter, the classification scheme for forest institutional regimes (typically including production, (watershed) protection and (biodiversity) conservation forests) is a major constraint, especially where the current situation on the ground no longer matches the planned situation and/or when classifications were imposed that from their start clashed with local use and claimed rights. Fay and Michon (2005) argued that in redressing forestry institutions, forestry regulatory frameworks may in parts of the landscape (especially where production is prioritized) best be replaced by an agrarian one. In name, community-based forest management has achieved a higher profile. However, from a community perspective, current forest tenure reforms are still limited in effectiveness by the restricted nature of the area that falls under their regime, the types of use that are allowed and the bureaucratic procedures (Larson and Pulhin 2012). Southeast Asia is no exception in this respect.

In Indonesia, the first significant progress in recognizing agroforests as successful examples of local resource management that should not be burdened by misinterpretations that they represent natural forest came in the Krui landscaper at the west coast of Lampung (Kusters et al. 2007). This breakthrough helped in framing further legal options when the Forestry Law was revised, after the political transition to a democratic government. The next steps in making community-based forest management applicable in a coffee agroforestry landscape in a watershed protection setting were initiated in Sumberjaya (van Noordwijk et al. 2019i). A rubber agroforest landscape at the edges of the Kerinci Seblat National Park in Lubuk Beringin became the first to get 'village forest' (or 'hutan desa') rights within this protection forest category (Akiefnawati et al. 2010). Other locations followed, although at a slower pace than envisaged, and in those that had obtained rights, a general sense of disappointment was recorded, that active restoration and use of the area remained burdened by procedures and rules (de Royer et al. 2018). A positive exception may be Lubuk Beringin that was able to convert its recognition and status to become a local focus for water-based tourism, with economic opportunities for especially women and youth. Examples can be found elsewhere in Southeast Asia of how indigenous agroforestry has facilitated restoration, despite not being recognized in existing regulation (Cairns 2007, 2015).

11.3.5 Drained Peatlands

Peatlands were mostly avoided in early human settlement patterns in Southeast Asia, as access is not easy, land clearing does not result in fertile soils and the subsidence after clearing makes areas even more vulnerable to flooding (van Noordwijk et al. 2014). Local drainage to transport logs became enlarged for canals to drain peat water. Once dry, peat soils shrink (causing the surface level to subside) and don't easily rewet, making them susceptible to fire. At a landscape scale, peat fires, which don't burn hot and clean, cause a large amount of haze that is toxic to all living organisms. Moreover, subsidence implies the area becomes even more vulnerable to flooding in the rainy season. On the shallower edges of peatland, part of the soil (especially that with a mangrove history) developed the acid-sulphate syndrome when the pyrite concentrations in deeper layers became aerated and extremely acid. Large-scale plantation development only became economically attractive when other land became scarce (and complex by the land tenure conflicts that often emerged), and technical options for deep drainage became available and attracted resources from national and international 'development' agencies. Many of these projects failed, as acid-sulphate soils developed, subsidence disturbed the drainage systems and the drainage dramatically increased vulnerability to fire.

Sago, a wetland-adapted palm, has been an important resource for local food and marketable products in various parts of Southeast Asia, but it has lost much of its ground, when the wetlands where it grew were converted to paddy rice fields (as documented for SE Sulawesi, for example, by Kelley et al. 2017). Elsewhere, sago stands were replaced by that of another palm, less tolerant of wet peatland conditions: *Elaeis guineensis* (oil palm). On shallower, sapric peatlands, such conversion was economically attractive (though the initial investment in drainage was higher than that for non-peat areas), on fresh forest peatlands, the conversion was a financial as well as economic disaster (Veloo et al. 2015).

Current restoration primarily depends on rewetting and canal blocking but faces mixed responses from local communities, while the mandated restriction on drainage in plantations (requiring groundwater levels to be no deeper than 40 cm) are not easy to achieve in practice with existing (tree) crops (Khasanah and van Noordwijk 2019; Tata 2019b). In this context, there has been strong interest in 'wetland agroforestry' as part of (or relative of) 'paludiculture' (Widayati et al. 2016; van Noordwijk et al. 2019e). The number of local tree species that can be used in wet peatland agroforestry, however, is still limited (Tata et al. 2018).

As the haze resulting from peatland fires became recognized as a major human health hazard, besides disturbing public and economic life, prevention of haze episodes as experienced in 2015 became a government priority (with targets that events at the time of writing in 2019 show have only been partly achieved). Revisions of provincial land use and 'green economy' development plans became a major target for a more coordinated government prevention plus restoration response (Box 11.5).

Box 11.5 Prioritizing Peat Restoration Opportunities in S Sumatra (Indonesia)

South Sumatra was a major part of the 2015 land and forest fires in Southeast Asia, competing with Riau and Jambi as the three peat-rich provinces of Sumatra (Ekadinata et al. 2013; Tata et al. 2015; Dewi et al. 2015). When the Peat Restoration Agency (Badan Restorasi Gambut—BRG) was created and developed its Peat Ecosystem Restoration Plan (Rencana Restorasi Ekosistem Gambut or RREG), the province was a logical target. Understanding the driving factors of peat degradation is instrumental in managing and restoring degraded peat. At national level, the Ministry of Environment and Forestry has launched a regulation on peat ecosystem protection and management plans applicable to all peat hydrological units (which include peat domes and their transitions to rivers) in Indonesia. In South Sumatra, the driving factors cover three of the five aspects mentioned in Fig. 11.2: rights (policies and policy gaps on land allocation and management, especially for large scale plantations), knowledge on land use practices (lack of awareness and knowledge to manage peatland sustainably, related to the socio-economic conditions of local people), and markets (logging concessions, illegal logging to meet the demand of pulp mills, oil palm and fastwood plantations). It had negative impacts on the other two: local health (by the loss of clean air as local ecosystem service) and loss of global services (C emissions, biodiversity loss). The three groups of drivers identified induce pressures on (agro)forest conversion, especially through the construction of canals to provide easier access to peatlands and/or drain them, with associated social and tenurial conflicts. Smallholder farmers also contribute to worsening the fire risks through their traditional rice planting using fire for land clearing (*sonor* systems), which produce quite low economic benefits (Suyanto 2007).

The process in developing the RREG consisted of (i) diagnostic process on the baseline condition of peatland in South Sumatra, particularly in districts Musi Banyu Asin and Ogan Komering Ilir, and (ii) zoning and medium-term peat restoration planning. The first-level zoning of the peat hydrological unit categorizes two main functions: protection (protected zone) and production (cultivation zone). Further, the second-level zoning was conducted based on the typology of the degradation level and the drivers of degradation, to ensure

(continued)

Box 11.5 (continued)
a more targeted action plan in each setting. Figure 11.11a presents the resulting zonation of conservation, protection and production areas. Figure 11.11b shows the typology of peat hydrological subunits based on function, fire risks, deforestation and land use changes, socio-economic conditions and access. For each of the types identified, main actions for interventions are proposed within three categories: (i) community awareness-raising programs, (ii) institutional capacity development and (iii) sustainable livelihood options. Restoration actions involve the (partial) closure of drainage canals, reliance on natural or assisted natural regeneration and/or planting of trees that tolerate wet conditions in their root zones and don't depend on drainage below the now-mandated 40 cm below the soil surface.

The RREG development proved to be useful not only in terms of the output but also through its inclusive planning process that increased awareness and built social capital among the stakeholders. To our knowledge, South Sumatra RREG is the only document that was produced inclusively with a provincial team. South Sumatra RREG has been published in 2019 by BRG, and South Sumatra Government Regulation has been issued and enacted.

11.3.6 Converted Mangroves

Part of the human victims of the December 2004 tsunami could have been avoided if people would have not lived at the coastline, especially in places that had been converted from mangroves, or in zones directly behind mangroves where the protective effect of this vegetation had been diminished by the creation of aquaculture, mostly shrimp ponds (Budidarsono et al. 2007). Elsewhere, other coastal tree-based vegetation was found to have a similar effect, proportional to the direct flow resistance provided by trees (Bayas et al. 2011). From this analysis, it is understandable that initial 'restoration' efforts after the tsunami focussed on mangrove restoration. Despite considerable planting effort, the success rate of re-establishing mangrove was, however, small (van Noordwijk et al. 2019e), as issues of property rights and alternative livelihoods were not simultaneously addressed. In other contexts, with longer timeframes for preparation, mangrove restoration has had a mixed and partially contested success rate (https://oceanwealth.org/applications/mangrove-restoration/; Lovelock and Brown 2019). In the coastal areas affected by the tsunami, establishment of a diverse, economically attractive tree cover has had more success than those targeting mangroves specifically.

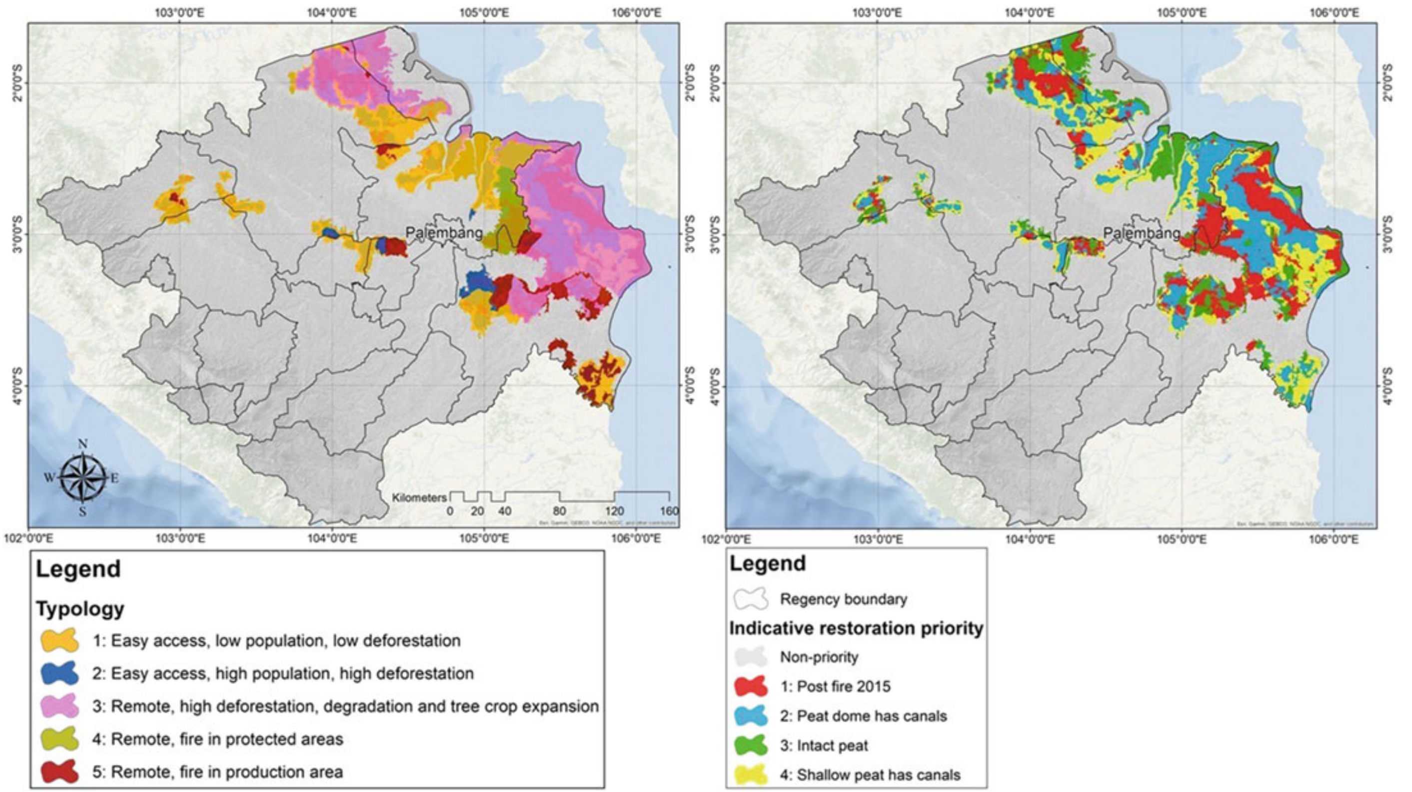

Fig. 11.11 Intervention maps of peat ecosystems restoration: (**a**) zonation and prioritization of conservation, protection and production functions; (**b**) typology of fire risks, degradation risks, socio-economic conditions and access

11.3.7 Disturbed Soil Profiles, Including Ash Deposition and Ex-mining Sites

Surface mining for coal and metals and the overhaul of river sediments in search for gold deposits affect relatively small areas but leave behind deep scars (Fig. 11.12) that can take decades or centuries to become part of landscapes with positive functions.

Such mining provides short-term employment and some revenue to local police and local government but otherwise leaves substantial social costs of a disturbed environment. Where mining is more technically advanced and planned, restoration of the remaining (or reconstructed) soil profiles is mandated as part of mining permits. Some of the soils can still have high metal contents and be unsuitable for crops for human consumption; in such cases, timber production can be the most economical alternative land use. Elsewhere, agroforestry as a provider of local food is possible.

Box 11.6 describes a case study of sand mining on volcanic slopes where agroforestry development for mid-slope positions has to be part of the landscape-level solution to avoid further degradation and assist in the restoration of damage already done. In this case study, the local sand mining was found to interact with climate change and loss of biodiversity (Hairiah 2018).

Fig. 11.12 Mining effects in Bungo district (Jambi, Indonesia). (**a**) A scar left behind when a species-rich rubber agroforest (studied by ICRAF researchers) became converted to an open-cast coal mine as the deeper carbon stocks had more market value than those related to current vegetation; (**b**) converting of subsoil white sands to a slurry, passed over a gold retrieval filter, before left of the soil surface (Photo credit: Meine van Noordwijk/World Agroforestry)

Box 11.6 Sand Mining on a Volcanic Mountain Slope

Volcanic eruptions not only disrupt adjacent land areas where volcanic ash is deposited but also create temporary employment as the sand-sized fraction in the riverbed can be extracted as building material. More disruptive than that, older sand deposits in the landscape can also be mined, leaving land behind without any topsoil. A recent study of the Bangsri subcatchment of the Brantas basin (East Java, Indonesia) on the western slope of the active Semeru (Mahameru) mountain (highest top on Java) showed the challenges this type of sand mining creates for any restoration or subsequent use of this part of the landscape. The upper slopes in the subcatchment are part of the Bromo Tengger Semeru National Park (TNBTS), with the mid-slope zone mostly classified as production forest (managed as part of the Perhutani estate) or agroforestry (owned and managed by farmers) with partial or 'closed' canopy. Land use systems (LUS) in the lower slopes are monoculture agriculture and settlements that tend to lead to an 'open' canopy. The area was selected as pilot for a national scheme to combine the land restoration agenda of the United Nations Convention to Combat Desertification (UNCCD) with the climate change adaptation agenda of the United Nations Framework Convention on Climate Change (UNFCCC). Details of a diagnostic study were provided in Hairiah (2018). There is evidence of a wetter and more variable rainfall regime that, combined with the poorly consolidated volcanic ash, implies a high risk of landslide disasters and high sediment concentrations in the river. The diagnostic study found that climate change effects on local livelihoods are exacerbated by the sand (volcanic ash) mining activities, operated by communities living in and outside the Bangsri watershed.

According to focus group discussions (FGD) and interviews with farmers, sand mining is, for the short term and at current prices, indeed more profitable than farming. However, the long-term decline of usable agricultural land increased pressures on the mid-slope parts of the landscape. After sand mining, despite efforts to bring back topsoil, low macropore connectivity inhibits infiltration and the development of plant roots. Production costs on such land are high and yields low. It became clear that for the watershed as a whole to regain the resilience it needs, the longer-term costs of sand mining will have to be recovered from those who benefit in the short term, likely reducing the pressure. This requires coordination between the local community, village authorities and watershed authorities, dealing with the current external beneficiaries. Such measures need to be accompanied by labour-absorbing efforts in the middle-zone agroforestry in the landscape where local water storage increases opportunities for vegetable crops under partial tree canopy (Fig. 11.13).

Fig. 11.13 (**a**) Sand mining and (**b**) the soil profile it leaves behind; (**c**) agroforestry as a provider of food, firewood and cash income; (**d**) development of water storage for small-scale irrigation of vegetables under tree cover as a major alternative to involvement in sand mining (Photo credit: Kurniatun Hairiah/Brawijaya University)

11.4 Two Overarching Concerns

As indicated in Fig. 11.5, two aspects of degradation and restoration concerns operate at a more aggregate scale than the syndromes discussed so far: hydrological functions and supply sheds for value chains at risk.

11.4.1 Disturbed Hydrology

A recent review of the role of agroforestry in 'nature-based solutions' to the regular and dependable supply of water of good quality (van Noordwijk et al. 2019g) discussed the scale relations and trade-offs, both upstream-downstream in watersheds and upwind-downwind in precipitationsheds (Ellison et al. 2019). While on small islands agroforestry is a natural concept for integrating land use (Van Noordwijk 2019), elsewhere, agriculture tends to be the user whose needs get prioritized and (restored) forests the supplier of water, to be supported by environmental service policies (Minang et al. 2019). Five aspects of vegetation (leaf area index throughout the year (phenology), litter layer, soil macroporosity, rooting depth and possible influences on rainfall) are now understood to govern the main hydrological functions (Jones et al. 2019) and respond over different temporal and spatial scales to land cover and land use change. As a point of reference for attributing floods and droughts to 'degradation', trees can be read as in history books that, through their growth rings, allow reconstruction of frequency and severity of past climate variability (Chen et al. 2019).

The main 'degradation' issues that trigger restoration activities remain concerns over water quality (sediment load), short response times to extreme rainfall events causing flooding by the lack of buffer functions and limited recharge of groundwater reserves. Interactions within a watershed between degrading or restoring hillslopes, riverbeds and surrounding riparian flow buffering areas are well understood in eco-hydrological models, but attention in restoration still tends to go to the hillslopes rather than downstream buffering functions. Some new metrics (van Noordwijk et al. 2017) allow the inclusion of agroforestry interventions in watershed restoration planning. In terms of water quantity, the increase in demand by trees with a different phenology to native vegetation remains a concern. Recent data analysis for the increase of rubber (*Hevea brasiliensis*) expansion in mainland Southeast Asia showed that impacts depend on the elevation at which conversion occurs, as well as the nature of the vegetation replaced by rubber plantations (Ma et al. 2019).

A quantitative diagnosis was also found to be needed to clarify the relative importance of different altitudinal zones on the Rejoso watershed, a planned source of piped drinking water for Indonesia's second largest city. Zone-specific agroforestry interventions were proposed and are currently being tested. Social differentiation was also noted, with a test of group-level versus individual contracts for watershed restoration at high and midlevel land uses ongoing (Leimona et al. 2019).

11.4.2 Supply Sheds at Risk

Another entry point for higher-level concerns over degradation and a potential source of co-investment in restoration have become the value chains of commodities produced in tropical landscapes. Concerns over rising prices due to shortfall of production in degrading landscapes interact with concerns of global consumers who don't want to be (or feel) responsible for the degradation that is reported in the press as a consequence of their consumption patterns. With these concerns, the response of 'certification' has become important in several (but not all) tropical commodities, with mixed effects on 'shifting blame' as well as 'resolving issues' (Leimona et al. 2018).

Where consumer boycotts and certification response represent a top-down response, there is also an increase in its bottom-up complements, especially where 'jurisdictional' approaches take 'green growth' initiatives, and articulate regional identity as a brand that can be dynamically managed to interact with the outside world and its shifting concerns and standards. Agroforestry as basis of the production of tropical commodities coffee, cacao, rubber and even palm oil (Slingerland et al. 2019) as well as energy (van Noordwijk et al. 2019f) can tell an attractive story that combines social and ecological concerns. Emerging global assessments of the economics of land degradation (Nkonya et al. 2016) have an interesting challenge to combine all such costs and benefits. The range of methods required to help agroforestry meet its full potential in such issues keeps expanding (van Noordwijk and Coe 2019).

11.5 Discussion

The 'forest transition stage' information of site-level studies to issues and solutions has some predictive value for the type of interventions that are most appropriate (Table 11.3): sorting out rights issues and focussing on market access in the early stages of transition, supporting nurseries of excellence and diversity in the middle and supporting soil and water interventions on the later stages. Yet, as a 'theory of place' underpinning 'theories of change', the current forest transition stage typology needs further refinement.

Across all the 'degradation syndromes' studied, we found strong confirmation that at least five of the six 'aspects' in Fig. 11.2 are important: (1) local institutions and motivation, (2) rights and their impacts on who is using land, (3) land use practices and associated knowledge and knowhow, (4) markets for inputs and outputs and (5) local environmental services (often the starting point for 'degradation' assessments and often related to disturbed hydrology). In the absence of strict law enforcement, de facto rights matter more than formal ones, as the Krui example showed for Indonesia (Kusters et al. 2007): the recognition by forest authorities of the *damar* agroforests as farmer-made meant that the formal procedure for individual farmer permits was not deemed necessary. This is similar to the Niger case of farmer-managed natural regeneration where practice was ahead of formal recognition (Garrity and Bayala 2019). The recently adopted ASEAN agroforestry policy guidelines (Catacutan et al. 2019) provide a conducive environment for targeted actions for inducing change at the landscape level but only if bottom-up initiatives can connect with such top-down support.

Less clarity was obtained on aspect 6. Global connectivity, where it seems arbitrary and outside of local control whether or not global discourses pick up on the issues that are locally identified. This has led to disappointment in developing payments for ecosystem services (PES) schemes (Wunder et al. 2008) and the lack of success stories for reducing emissions from deforestation and forest degradation (REDD+), despite all the preparatory efforts that went into this idea (Agung et al. 2014). There has been more progress with locally led co-investment schemes for environmental services that focussed on the aspect of the disturbed hydrology (Leimona et al. 2015), although metrics for performance-based arrangements remain elusive (van Noordwijk et al. 2016). Co-investment has become a central paradigm for the various stakeholders to define their take on the common but differentiated responsibility for degraded landscapes (Namirembe et al. 2017). However, it remains an art that is difficult to grasp for 'planners'.

Where 'restoration' is to be managed as a program or project, it requires 'metrics' as markers of progress and clarity on targets. The four intensities of restoration (Box 11.1) clarify that 'restoration' has no fixed endpoint, other than through engagement of and often co-investment by external stakeholders bringing issues within the reach of farmer-level ecological intensification within a land use system. A recently introduced metric (van Noordwijk et al. 2018) of the 'multifunctionality land equivalent ratio', LER_M, (the amount of land needed to provide all of the products and services a land unit provides, if all functions would be segregated into

Table 11.3 Overview of characteristics for the seven degradation syndromes in the SE Asian landscapes studied (relative importance is indicated by the number of asterisks) and issues identified

Degradation syndrome and forest transition (FT) stage of landscapes studied	I. Community-driven motivation to reverse degradation	II. Rights and tenurial security	III. Means, knowledge of and skills	IV. Markets for inputs and outputs	V. Local and downstream, ecosystem benefits	VI. Global ecosystem benefits
SDG links	2,3,4,5,10,16	5,10,16	4,5,8,17	1,2,8,9,12	3,6,7,11	13,14,15,17
A. Degraded hillslopes FT 3–6	Landslides, flash floods	Local bylaws, sharecropping CBDR*	Supporting functional tree diversity*	Limited quality of tree nurseries*	Water quality and flow persistence**	Impacts on downstream wetlands, coral reefs*
B. Over-intensified monocropping FT 3–5	Relationship with agricultural input enterprises	Contract farming(*)	Soil health management**	Risk management**	Foregone LER_M benefits*	Crop-specific certification(*)
C. Fire-climax grasslands FT 3–6	Fire risks, relationship with forestry enterprise	Tenure, fire as weapon**	Local fire control*	Risk for tree crops*	Escaping fires**	C emissions*
D. Forest classification and local rights FT 2–4	Legality of agroforestry, respect for communities	Ineffective forest tenure instruments**	Respect for local knowledge(*)	Often 'remote' locations(*)	Local ES taken for granted**	Global biodiversity benefits*
E. Drained peatlands FT 2–3	Haze, relationship with plantation enterprises	Land preparation without burning; rewetting mandates, enforcement ~peatland hydrology**	Rewetting techniques, water management, paludiculture options**	Shortage of paludiculture products*	Haze control, fire risks**	Transboundary haze control agreement globally relevant C emissions**
F. Converted mangroves FT 3–6	Flood risk, relationship with shrimp and charcoal enterprises	Existing protection rules ignored*	Options to 'work with nature'*	Emerging certification**	Coastal fish breeding grounds**	Protection of adjacent coral reefs**
G. Disturbed soil profiles FT 5–6	Relationship with mining enterprise	Uncontrolled local mining practices**	Recovery-remediation techniques**	Markets for 'mining'(*)	Impacts on hydrology*	Pollution of downstream wetlands (*)

specialized ways of providing the same) may in future serve as a single metric that can mark progress. Multifunctionality is, like beauty, in the eye of the beholder: what is improvement for one (e.g. transforming mixed rainforest to a fastwood plantation) can be degradation for somebody else.

While SE Asia stands out in its current prevalence of agroforests, nuclei of similar farmer-developed tree-based land uses are found elsewhere as well. The current analysis for SE Asia may have to be followed up by a global comparative study. Globally additional syndromes (including overgrazing, overharvesting) will have to be included, but the same six aspects, the four intensities, the SDG framework and proposed multifunctionality performance metric are likely as relevant globally.

When we can combine a 'theory of place' (at the what? where? level of system states), with a theory of change (impacts on stakeholders leading to responses and efforts to change drivers and pressures), we may see opportunities for a 'theory of induced change' that clarifies entry points for external stakeholders to 'nudge' and 'co-invest' in the local socioecological system (Minang et al. 2019), transforming from 'degrading' to 'restoring' phases. The rapid succession of 'theories of induced change' associated with international initiatives such as integrated conservation and development projects, reduced emissions from degradation and deforestation, global restoration commitments (Bonn challenge), ecosystem-based adaptation, community-based adaptation, climate-smart agriculture or green growth is hard to understand at the grassroots level and has supported a new class of intermediaries and entrepreneurs in the landscapes, who often lack the deeper understanding of local socioecological systems needed to make real progress (Langston et al. 2019; Minang et al. 2019).

The SDG framework is probably still the best platform for discussing and increasing coherence, as the SDGs can be mapped to all six aspects identified, and allows primary agenda holders (at landscape, national and global scales) for all separate SDGs to come together to make progress for each set of indicators.

11.6 Conclusions

All six aspects identified ((1) local institutions and motivation, (2) rights, (3) knowledge and know-how of land use practices, (4) markets for inputs and outputs, (5) local ecosystem services and (6) global connectivity) can be a starting point for restoration interventions, but progress is typically limited by several (or all) of the others, with the first as major challenge where priority setting has been essentially top-down. Entry points such as integrated conservation and development projects, reduced emissions from degradation and deforestation, global restoration commitments (Bonn challenge), ecosystem-based adaptation, community-based adaptation, climate-smart agriculture or green growth are all permutations of the current Sustainable Development Goals agenda and are best seen as a continuum, rather than as silo's competing for donor attention. They all need to deal with the current drivers of degradation and find ways to facilitate and support locally led recovery of landscape multifunctionality. The SE Asian experience with agroforestry, despite its lack of formal recognition in formal agricultural or forestry policies until recently, offers lessons to learn across a wide range of 'degradation syndromes', acknowledging that a more careful and location-specific diagnosis has to be the first step towards successful interventions.

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12 Community-Based Peat Swamp Restoration Through Agroforestry in Indonesia

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Abstract

Ecological restoration efforts in Indonesia have proliferated since the severe forest and peat fires in 2015. These efforts accommodate socio-economic sustainability and focus on reducing anthropogenic pressure on the ecosystem. As a sustainable livelihood option, agroforestry can enhance community welfare and restore the degraded ecosystem. Local communities in Indonesia possess knowledge related to the management of the ecosystem and practice many traditional agroforestry systems, e.g. local timber gardens—*repong damar*, *simpukng* and *tembawang*. This traditional knowledge is evaluated based on the centuries of human interaction with the environment. This chapter reviews various agroforestry systems and their local values in a peat swamp ecosystem useful for peatland restoration. We identify various traditional agroforestry systems that can be practiced in a degraded peat swamp area and to restore the associate ecosystem. Building on this, we suggest future approaches, focusing on advocacy and dissemination of traditional knowledge and practices. Further, a study on rebuilding and documenting traditional knowledge and agroforestry practices in a peat swamp ecosystem is crucial.

Keywords

Agroforestry · Livelihood · Ecological restoration · Peat swamp · Traditional knowledge

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12.1 Introduction

Indonesia has the largest share of tropical peatland in Southeast Asia. This stores over 57 gigatons of carbon (Page et al. 2011). However, Indonesia's peatland has been subject to serious anthropogenic pressures across different spatio-temporal scales; for example, peatland conversion into agricultural uses (Osaki et al. 2016a, b; Hergoualc'h et al. 2017), mining (Dommain et al. 2016) and logging (Dommain et al. 2016; Hergoualc'h et al. 2017). This has left much of its peatland dried, degraded and prone to fire. In 2015, Indonesia experienced severe forest and peatland fires, emitting 1.5 billion tCO_2 (Field et al. 2016) and caused ~ USD 16 billion loss (Glauber et al. 2016). Indonesia is the fifth largest carbon emitter in the world largely due to the destruction of ancient peatland forest (Joosten 2009).

Ecological restoration of degraded tropical peatlands is currently widely practiced in Indonesia. As a part of the restoration effort, in 2016, the Government of Indonesia established the Peatland Restoration Agency (BRG) through Presidential Decree No. 1/2016 to facilitate 2 million hectares of peatland restoration by 2020. Many actors are actively taking part in the restoration process. A study by Puspitaloka (2017) reported there were several peatland restoration projects managed by different stakeholders in Central Kalimantan. Although facing different socio-economic and ecological challenges, the peatland restoration projects incorporate similar socioecological aspects into their goals and practices, i.e. enhancing community wellbeing through voluntary participation and reducing anthropogenic pressure on the ecosystem by developing alternative livelihoods for local communities.

As the drivers of peatland degradation are related to livelihood, restoration efforts should be focused on exploring alternative livelihoods (Dohong et al. 2017). In this aspect, agroforestry practices can be applied as a promising restoration technique, because it not only enhances biodiversity and associate ecosystem but also reduces the need of forest clearance by allowing communities to grow on farm forest products (Rahman et al. 2017). Agroforestry products also have social and economic advantages, i.e. they promote social cohesion and have high monetary value (Rahman et al. 2017). Therefore, in guidelines to restore peatland, the Indonesian Ministry of Environment and Forestry recognized agroforestry as the best practice for peatland and highly recommended system in the cultivated zone of the forest lands.

Local communities in Indonesia, in Sumatra and Kalimantan, for example, are living in the peat swamp area in centuries and developed their knowledge of managing local ecosystem based on its various biophysical characteristics. Traditional agroforestry practices are among them as an important ecosystem management tool that includes local timber garden practices, such as *repong damar*, *simpukng* and *tembawang*. As different agroforestry systems present different livelihood and restoration opportunities, this chapter reviews different types of agroforestry systems and their local values in a peat swamp ecosystem.

Table 12.1 Search sites, key words and inclusion criteria to generate targeted information from literature review used in this study

Search sites	Key words and search phrases	Inclusion criteria
Google Scholar, Mendeley, Scopus, Web of Science	'Agroforestry', 'agroforestry Indonesia', 'agroforestry peatland', 'agroforestry peatland and Indonesia', 'agroforestry livelihoods', 'agroforestry and ecosystem', 'agroforestry benefits', 'agroforestry and land restoration', 'paludiculture', 'silvofishery', 'traditional agroforestry', 'traditional knowledge', 'peat swamp', 'peat swamp ecosystem', 'peatland restoration'	Information on agroforestry based on ecosystem and traditional values in a peat swamp ecosystem in Indonesia

12.2 Materials and Methods

This chapter is based on a literature review of both the peer-reviewed and grey literature. Using selected key words and phrases (Table 12.1), relevant literature was gathered from the internet using scientific research search sites, i.e. Google Scholar, Mendeley, Scopus and Web of Science. The review was conducted from August to December 2018. At the outset of the review, the inclusion criteria (Table 12.1) were necessarily rudimentary. We refined the search by examining the abstracts and contents of the retrieved articles to evaluate their relevance to our study.

The relevant information was carefully compiled point by point and interpreted using the narrative qualitative analysis method. The analysis process is designed to scrutinize relevant concepts from textual data in a transparent subjective way. Careful attention was paid for a more discursive interpretation and to provide a view of reality (as presented in the next sections of this chapter) through a process of decontextualization and recontextualization with appropriate scientific order.

12.3 Peat Swamp: Perception of Local People and Migrants

> ...May all [plants] planted here, coconut tree, pinang [*Areca catechu*], aren [*Arenga pinnata*], sagoo, and all kinds of trees, the fruits are edible, as well as haur bamboo, waluh, and pattum, et cetera; and may all other plants with the dams and ponds, and all of good deed that I've gave [contributed] can be enjoyed for the benefit of all creatures; the one that can moved around and ones that cannot, and may this would be the best path to achieve happiness ... (Talang Tuwo Inscription, 684)

Above is a fragment of Talang Tuwo, an inscription from the ancient Srivijaya Empire describing sustainable environmental management for the prosperity of the people (Rahmad 2016). The inscription was written for the Sri Ksetra Garden, which was inaugurated by Ḍapunta Hyang Śrī Jayanāśa, Maharaja of Srivijaya, in 684. It documented multiple species, which were cultivated in earlier centuries. Srivijaya had a strong maritime culture, with an integrated management system from the hinterland to the coast to the high seas. The strong maritime culture in Kedatuan Srivijaya (the capital) influenced the overall *Mandala* (states) (Wolters 1967; Manguin 1993). This ideology was inherited by later generations, with the local community viewing the peat swamp landscape as an integral part of the sea (Masuda et al. 2016). Furukawa (2004) noted in his study of Melayu people that "it sometimes seems as if the whole Melayu world is one single town, a maritime metropolis spanning the sea". Momose (2002) described different local community livelihoods related to the physical characteristic and geographical position of peat swamp ecosystems.

> . . .Take a piece of land; if it feels warm and fragrant it indicate a good place for dwelling, a lot of blessings to that earth; plants cultivation will grow well, diseases will be away, many traders would come, conflict would be away; . . . ; prosperity will come (and) difficulties will be away. A fragrant soil, but cold, less blessings to that earth, the evil as the same as the wellness. When the soil is warm but have no fragrant, more evil than its good. When the soil is cold, and the smells foul and stink, the land is wretched, there is no goodness on it; it will lead to a havoc. . . Hikayat Banjar (Ras 1990)

The Borneo–Malay chronicle, *Hikayat Banjar* (Ras 1990), recorded a traditional knowledge system for determining areas for suitable for living and cultivating plants. The local community tends to choose warm and good smelling soil for its settlement area. Fragrant terms, i.e. good-smelling soil, refer to the chemical substances within the soil. A distinct, unpleasant odour is often found in waterlogged and deep peat soils, indicating high levels of hydrogen sulphide (H_2S), a toxic substance to plants (Noor 2004; Umar et al. 2014). Terms related to the temperature of the soil, i.e. warm and cold soil, indicate decomposition, where the components are likely to decompose more rapidly in a higher temperature soil, which also increases soil nutrient availability (Nusantara et al. 2014). Hence, the traditional community knowledge determines suitable land for plant cultivation: land with low hydrogen sulphide (H_2S), marked by fragrant soil, and high nutrient availability, marked by warm soil. The mud depth to the elbow (about 40–50 cm) is also considered to determine an area's suitability for farming (Umar et al. 2014). Peatland that is not suited to crop cultivation is traditionally managed by the community for other livelihood activities, e.g. fish aquaculture, water buffalo, collecting goods such as timber and non-timber forest products (NTFPs).

Earlier peat swamp community livelihoods were based on collecting goods, logs, fish and NTFPs from the natural giant tree environment (Furukawa 2004). Based on their biophysical characteristics, lowland plains are divided into three different zones: flood, central and tidal (Furukawa 1994). While Masuda et al. (2016) describe different community livelihoods based on geographical position and biophysical characteristic of lowland plains, namely, *pangkalan* villages, *muara*/*kuala* villages, spontaneous-migrant villages and fishing villages.

Pangkalan village people, who live in the flooded zone, rely on fish and agricultural practices in hilly areas for their livelihoods. People, who live in the central zone, between *pangkalan* and *muara/kuala*, have a strong bond with peat swamp forests and rely on fisheries, timber and NTFPs for their livelihoods. Agriculture is often practiced in *muara/kuala,* a confluence of two or more rivers, located close to a shore or the tidal zone, where nutrients from the river are deposited. Fishing village people who live in the mangrove and along the shore area often rely on fishing from the mangrove and high seas (Furukawa 1994; Momose 2002).

Plant cultivation in the tidal zone has been discussed since the 1980s (Collier 1979, 1980; Collier et al. 1984). However, an understanding of the different community livelihoods and the biophysical situation is needed to find the best formulations for an agroforestry system for restoration in different degraded lowland plains areas.

To support sponsored-migrant livelihoods, while also boosting food security, the government has invested in agricultural development, including oil palm plantations (Budidarsono et al. 2013). Many drainage canals have been built to develop plantation and agricultural areas in unorthodox zones for farming to boost agriculture and non-native tree species production. The program had catastrophic results, with forest and land fires, peat subsidence, seawater intrusion and abrasion. The Mega Rice Project (MRP) has also been systematically responsible for conversion of large areas of peatland in the past decade.

In contrast to the local community, government-sponsored migrants often see peat swamp as potential agricultural land (Furukawa 2004; Masuda et al. 2016). This perception was common among the Java and Bali government-sponsored migrants. Mechanized agriculture, including using tractors and hoes, speeded up soil loss and compaction in peatlands. Saltwater in the tidal zone during the dry season has prevented the migrant farmers from applying their knowledge of farming from Java and Bali (Collier 1980). Therefore, in this paper, we focus on the reintroduction of ecosystem-based agroforestry for peat swamp restoration.

12.4 Key Elements of Successful Traditional Agroforestry in Indonesia

Indigenous communities in Indonesia utilize peatland as a resource to produce food crops, fruits and spices (Osaki et al. 2016a). Medrilzam et al. (2013) considered the socioecological connection to be the key factor affecting forest cover changes in tropical peatland ecosystems. Therefore, the human dimension must be considered to ensure the long-term success of peatland restoration. Many community-based organizations have been formed to implement this restoration approach, for example, *Desa Peduli Gambut* (peat-care village) and *Masyarakat Peduli Api* (fire-care community). These initiatives use a novel, grassroots approach that actively engages local communities in ecological restoration, reconnecting humans with the environment (Leigh 2005). Leigh (2005) further argued that community-based restoration serves as an instrument for social change by engaging a committed group to address environmental problems at multiple scales.

In Indonesia, communities are involved throughout the restoration process. This includes building restoration facilities, seeking a more sustainable alternative livelihood and educating the community about fire-free land preparation. However, little is known on the extent to which current efforts incorporate sociocultural aspects, such as traditional knowledge.

Communities in Indonesia have practiced agroforestry since humans started to shift from hunting and gathering to cultivation (Rohadi et al. 2013). Many traditional agroforestry practices are found in Indonesia, for example, *parak* in West Sumatra, *repong damar* in Lampung, *tembawang* in West Kalimantan, *simpukng* and *kebun* in East Kalimantan, *talun* and *dudukuhan* in West Java, *amarasi* in East Nusa Tenggara and *tenganan* in Bali (de Foresta et al. 2000; Sardjono et al. 2003; Rohadi et al. 2013). Traditional agroforestry practices, such as *repong damar*, can resemble a natural forest ecosystem, in terms of plant and wildlife composition (Prahasto 2002; Wijayanto 2002). They also ensure water availability throughout the year and generate many other benefits (Wijayanto 2002). *Tembawang* successfully maintains forest structure and diversity, as well as sequestering large amounts of carbon (Astiani and Ripin 2016). Another traditional agroforestry system, *simpukng*, according to Mulyoutami et al. (n.d.), produces environmental and economic benefits from both cultivated and wild flora.

Traditional agroforestry practices in Indonesia have unique local characteristics. Here, we focus on *repong damar* in Sumatra and *tembawang* and *simpukng* on Kalimantan Island (Table 12.2). Although very little is known about the soil requirements of these traditional agroforestry practices, we primarily aimed to identify key elements supporting the development of community and alternative livelihoods. *Repong damar* or damar (*Shorea javanica*) agroforestry is a part of three production phases used by Krui farmers in managing agroforestry (Lubis 1997). The earlier phases are rice paddy and cash crop plantation. In the *repong damar* phase, Krui farmers grow a variety of perennials, such as damar, durian and petai, which take longer to produce a yield. The diversity of crops guarantees steady income for the household (Wijayanto 2002). It also helps to prevent overexploitation of the land by farmers, because the farmers have diverse sources of livelihood (Darusman et al. 2001). A study by Wijayanto (2002) showed the success of *repong damar* agroforestry with high diversity of crops and the compatibility of the crops and ecosystems nearby. Wijayanto (2002) further explained *repong damar* requires low capital input, yet in terms of economic contribution, it contributes from 70% to 100% of the farmers' income (Alviya and Suryandari 2006). In a sociocultural context, *repong damar* involves management by multiple generations of a family, so knowledge of the practice is well maintained. The ownership of *repong damar* agroforestry also represents social status, due to the possession of many resources, i.e. diversity of crops (Lubis 1997). The economic factor together with sociocultural and ecological influences, as argued by Lubis (1997), has shaped the perspective of Krui farmers that *repong damar* is a high-advantage, low-risk system, due to its diverse variety of crops (Lubis 1997).

Table 12.2 Key elements of traditional agroforestry practices in Sumatra and Kalimantan, Indonesia

Agroforestry type and example of cultivated commodities	Key elements of agroforestry practices	References
Sumatra Island		
Repong damar Examples of cultivated commodities: *damar*, *duku*, durian, *petai*, *jengkol*, *tangkil*, mangosteen, *kandis*	*Ecological aspects:* – Ecological suitability with other ecosystems nearby. – Diversity of crops minimizes the risk of crop failure and overexploitation while giving many other ecological benefits, such as ensuring water availability throughout the year. *Economic aspects:* – Contributes to household income/revenue and ensures household economic security. – Feasible with less capital input. *Social and cultural aspects:* – Management involves multiple generations of the family. – Knowledge of management passed down through generations. – Representation of social status, which encourages people to continue to practice the system.	Lubis (1997), Darusman et al. (2001), Wijayanto (2002)
Kalimantan Island		
Tembawang Examples of cultivated commodities: *tengkawang*, rubber, fruit-bearing trees, *nyatuh*	*Social and cultural aspects:* – Familiarity of the community with the practices. – Provides materials for cultural/religious rituals. – Involves customary laws and regulation to avoid exploitation and ensure equitable access to future generations.	de Oliveira et al. (2000), Roslinda et al. (2017)
Simpukng Examples of cultivated commodities: Ironwood, durian, betel nut, rattan and bamboo	*Social and cultural aspects:* – Customary rules to regulate the use and inheritance of forest. – Gender division of labour .	Mulyoutami et al. (n.d., 2009)

Tembawang is a traditional agroforestry practice found in West Kalimantan. It refers to an area owned by the indigenous community (Pahlevi 2015; Roslinda et al. 2017) where varieties of trees, including fruit-bearing trees, are grown (Prahasto 2002). According to Roslinda et al. (2017), *tembawang* is managed in a traditional, communal manner by the Dayak ethnic community. It has high species diversity and a multilayered structure. The main contributors to income are rubber, *tengkuwang* (*Shorea machrophylla*) and fruit (Alviya and Suryandari 2006). The community gains many benefits from *tembawang*, which, according to Roslinda et al. (2017), ranges from energy, food and medicinal plants to materials for cultural and/or religious rituals. Roslinda et al. (2017) further argue that the community had created and long been practicing *tembawang*; therefore, they are highly familiar with regulating utilization. The Dayak managing *tembawang* fulfil the needs of the current generation while ensuring equitable access to the resources through customary law and regulations, where the utilization of goods produced in *tembawang* are regulated by the community to avoid overexploitation (de Oliveira et al. 2000).

Simpukng, according to Wahyuni (2011), is a reserved area in the form of a forest island of mixed tree species such as rubber, rattans, ironwood and fruit trees. It functions as an in situ conservation area for ironwood, as well as many other plants. It was developed by the Dayaks of East Kalimantan who use *simpukng* for consumption, medicinal, domestic and ritual purposes (Mulyoutami et al. 2009). The Dayak manage *simpukng* under customary rules to regulate the use, as a part of their effort to control and avoid overexploitation. They perceive *simpukng* to be a common property where they can harvest the products for subsistence, but not commercial, uses. The customary law also specifies a gender division of labour, where women are responsible for collecting seeds, planting, weeding and storing products (e.g. firewood), as well as processing and selling products (e.g. fruits).

12.5 Reflecting Traditional Knowledge: Agroforestry System Options in Peat Swamp Ecosystems

In contrary to the coercion of cultivation practice against peat swamp natural ecosystem character which has devastated the environment, communities living around peat swamps have the context-specific knowledge to manage the ecosystem sustainably (Furukawa 2004). Here, we illustrate agroforestry practices that could be adopted applying local knowledge to ecosystem management.

12.5.1 Agrosilvo System

Agriculture is very limited in the peat swamp ecosystem and only practiced occasionally depending on the season and situation. Communities farm along riverbanks, particularly in *muara/kuala* (an estuary) where nutrients are abundant due to river flow. Agriculture in *muara/kuala* is based on tidal movements. A lesson from the past noted that plant cultivation in the peat swamp ecosystem is strongly advised in the “fragrant and warm soil”, which is commonly found alongside the riverbank in the back swamp and shallow peat.

The local community in Kalimantan practices *surjan* (alternating bed system) in the tidal zone area. Utilizing the tidal movement, water is managed using a one-way flow system with flapgates and/or dam overflows and depends on canal blocking (*tabat*) to manage the water level of the land. The system uses polyculture practice, where part of the land is dug (*tabukan*) for water-based plants, such as paddy cultivation, while part of the land is mounded up for crops or trees, such as *Citrus*

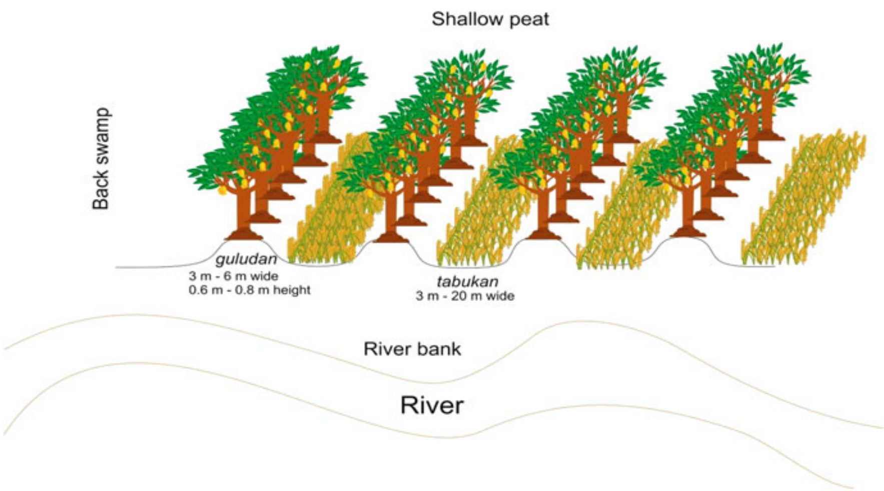

Fig. 12.1 *Surjan* system, traditional agroforestry in a peat swamp ecosystem, widely practiced in the tidal zone of Kalimantan

spp. and *Mangifera* spp., that require drier soil. An illustration of *surjan* is presented in Fig. 12.1.

Commonly, *surjan* agroforestry is built in the back swamp and shallow peat near the river. A *surjan* system should not be built if the peat depth exceeds 30 cm to avoid any destruction in the fragile ecosystem of peat. Water management is determined by flooding. The *surjan* system is recommended in areas that are flooded by large tides (*pasang besar*) (Susilawati and Nursyamsi 2014).

Study of Dakhyar et al. (2012) in Jambi revealed that a farmer's revenue under the *surjan* system with paddy and vegetables was about USD 652 per hectare. Balai Penelitian Pertanian Lahan Rawa (BALITTRA) noted a farmer in Barito Kuala, South Kalimantan, could get about USD 6809 per hectare per year using a *surjan* polyculture system based on *Citrus* spp. and paddy (*Oryza sativa*) (Yantirina 2018).

12.5.2 Silvofishery System

In peatlands, the recommended species vary according to the biophysical characteristics of the peat. The peat depth and water table condition during the rainy season are determining factors. Several studies have produced lists of species, e.g. Tata and Susmianto (2016) and Borchard et al. (2018); however, the characteristics of the biophysical condition should be considered for any application. Fish species should be selected according to water pH level and oxygen level (Huwoyon and Gustiano 2013).

Fish are an important commodity for peat swamp communities. Intact mangrove areas have high species diversity (Descasari et al. 2016; Indriani et al. 2009). There are about 60 fish species found in the acidic peat swamp ecosystem in South Sumatra

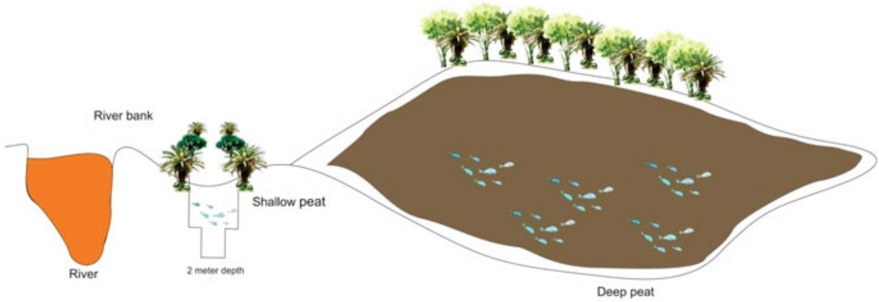

Fig. 12.2 Illustration of *Beje* agroforestry system (not to scale) (modified from Setiadi 2014)

and Kalimantan (Setiadi 2014). Fishing is integral to peat swamp communities' livelihoods; 14 different boat types and more than 40 fishing tools were identified in Malay–Banjar peat swamp community (Ideham et al. 2015).

In Kalimantan, people fished in a natural fish pond, *Beje*. *Beje* are artificial ponds that trap fish by utilizing the movement of water during the rainy season which usually spans from November to March, while fish often went to peat swamp forest for breeding during the rainy season, particularly in January and February (Fig. 12.2; Setiadi 2014). Practiced by native *melayu* Kalimantan (Banjar and Kutai) and adopted by Dayak, the pond is usually made in the form of a rectangle or square with length varying between 10 and 30 m and width 5–10 m. *Beje* ponds could be integrated into the agroforestry system. Cut wood and branches are also used to attract fish. (Rupawan 2006). The communities harvest the fish during the dry season when the water recedes. *Beje* needs no drainage system and requires wet conditions; hence, it will prevent peatland degradation and eventually prevent GHG emission (Setiadi 2014).

A study by Rupawan (2006) noted that the species occurring in the fish ponds were predominantly Anabantidae and Nandidae. Eleven fish species dominate the marsh area: *Sepat siam* (*Trichogaster pectoralis*), *Sepat rawa* (*Trichogaster trichopterus*), *Haruan* (*Channa striata*), *Papuyu* (*Anabas testudineus*), *Tambakan* (*Helostoma temminckii*), *Baung* (*Mystus nemurus*), *Singgaringan* (*Mystus nigriceps*), *Lundu* (*Mystus gulio*), *Lais lampok* (*Cryptopterus limpok*), *Lele* (*Clarias* spp.) and *Kakapar* (*Pristolepis fasciatus*). On average, a community produces about 880 kg/*beje*/year. While fish price varies between species, one *beje* could make IDR 650,000–7,900,000 per year (Rupawan 2006). In addition to *beje*, permanent fish ponds and fish cages could be built along the river and at the canal dams (Fig. 12.3).

Ducks and water buffalo (*Bubalus carabanensis*) are also widely bred, although the livestock choices are dependent on the landscape. Several areas, such as Bararawa of South Kalimantan and Pampangan of South Sumatra, are suitable for *B. carabanensis*. While breeding buffalo requires a large area for grazing, duck farming can be carried out in almost all conditions. The local breeding duck, *Itik alabio*, is fully grown after 5–5.5 months, can produce 220–250 eggs per year and continues to produce eggs up to 3 years (Cahyana 2017).

(a)

(b)

Fig. 12.3 Fish pond alongside canal in Desa Perigi Talang Nangka, South Sumatra (Photo © BAPPENAS (**a**), CIFOR (**b**))

Fish cultivation can be combined with tree and palm species as widely practiced by the community in the 1950s. The Indonesian government has released guidelines for sago (*Metroxylon sagu*) cultivation. The recommended spacing between plant clumps are 12 × 8 m or 16 × 8 m. Fish and/or duck cultivation is recommended for wetlands, such as peat swamp ecosystems. Multiple agroforestry products are used in traditional cooking; for example, *Kelesan*, widely known as *Pempek*, is a traditional dish made of fish, sago flour, duck egg and palm sugar of *Arenga pinnata* (Fig. 12.4).

Fig. 12.4 *Kelesan*, Palembang Darussalam Sultanate's royal cuisine, widely known as *Pempek* (Photo © Irawan 2018)

12.6 Challenges and Opportunities for Traditional Agroforestry Practices and Peatland Restoration

It is important to determine appropriate techniques for any cultivation activities, especially in fragile ecosystems, such as peat swamp. Failure to understand the ecosystem characteristics and altering the ecosystem to support food production using Javanese-style farming brought extreme stress and consequent disaster to the biodiversity. Traditional communities, however, practiced techniques that were in harmony with the characteristics of the ecosystem (Furukawa 2004), thus ensuring sustainability.

Aspects of traditional practices could be applied to modern agroforestry. These include consideration of ecological suitability, community familiarity with the practices, customary regulation and the sacred value of land.

Community adherence through self-organized governance could ensure the sustainability of resources (Ostrom 1990). For example, the self-governing community institution, *Marga*, in the Southern Sumatra, regulated its resources of *Nipah* (*Nypa fruticans*) to maintain sustainability (Collier 1979).

Secure land tenure and tree use rights are important for the successful implementation of smallholder tree-planting activities (Rahman et al. 2014; Tomich et al. 2002). Where they lack secure rights to use land and to harvest produce, smallholders are unlikely to plant or tend trees. In addition, without permanent land title, smallholder farmers are deprived of access to the credit required for the initial capital to invest in tree planting (Roshetko et al. 2007; Rahman et al. 2012). Policy reform to provide permanent land titles to local farmers is key to agroforestry adoption. In addition, a flexible policy by the institutions providing credit to support farmers who lack permanent land tenure could also facilitate this sustainable development.

Studies have demonstrated that smallholders generally face weak market linkages (Hammett 1994; Arocena-Francisco et al. 1999; Rahman et al. 2012). Poor accessibility to appropriate markets limits the profitability of smallholder tree farming (Shamsuddin and Mehdi 2003). There is a need for a market system for agroforestry products that increases farmers' awareness of and physical access to markets. User group cooperatives could play a role in supporting the smallholder, facilitating adoption, improving the supply chain of peat swamp ecosystem commodities and helping with market negotiations as a collective.

A support from culture base for ecosystem restoration is essential. Former President Suharto tried to apply a Mataram–Javanese farming culture to nutrient-poor fragile peat swamp ecosystems. While the Mataram style has been successfully applied in a rich mineral volcano soil, the same strategy brought devastation to the peat swamp ecosystem. At the same time, Melayu people with their inherited Srivijaya maritime culture and traditional knowledge have developed different techniques that survive and continue to be successful. It is crucial to ask, in the current context of free trade and a globally connected world, whether to follow market demand and introduce alien products into the ecosystem or promote the existing, and often abundant, commodities of peat swamps. A balanced approach is needed.

12.7 Conclusions

Incorporating human dimensions into restoration is crucial to counter the anthropogenic factors driving the degradation of the peatland ecosystem. Current restoration efforts include many community development programs focusing on developing alternative livelihoods and methods of cultivation on peat swamps. However, more consideration of sociocultural aspects should be made. In Indonesia, traditional knowledge and local wisdom related to the management and practice of cultivation on peatland and traditional agroforestry are readily available. This wisdom has accumulated over long periods of time through human–nature interaction. Traditional cultivation practices accommodate the biophysical aspects of the ecosystem and the sociocultural aspects of the people. Agroforestry practices with strong social, economic and cultural aspects benefit the community and ecosystem. Key elements of the success of traditional agroforestry practices in Indonesia include strong community laws and regulations, as well as institutions. Local knowledge is dynamic, evolving over time, and accepts new knowledge depending on the situation and need (Mulyoutami et al. 2009). It is still important to preserve traditional agroforestry practices to allow future generations to learn, reflect and draw key elements for successful natural resource management. While allowing traditional knowledge to flourish, newer institutions that cater to the current economy, facilitate technological improvement and develop producer-friendly market linkages will facilitate successful regeneration of peat swamp ecosystems.

Future advocacy and dissemination is crucial to enable the success of traditional practices to be replicated and scaled up. Studies related to designing alternative livelihoods for restoration, in the future, should focus on rebuilding and documenting traditional agroforestry knowledge and practice.

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13 Agroforestry to Sustain Island and Coastal Agriculture in the Scenario of Climate Change: Indian Perspective

Jagdish Chander Dagar, B. Gangaiah, and Sharda Rani Gupta

Abstract

There is about 620,000 km of coastline in the world, and over one-third of the total human population lives within 100 km of an oceanic coast. Though it has not been possible to come up with the exact number of islands, there are around 2000 islands in oceans in the world. India has a total coastline of 7516.6 km, out of which mainland coastline consists of 6100 km and islands' coastline consists of 1197 km. Indian coastline touches nine states and four union territories. In the scenario of climate change, these areas are vulnerable to frequent natural disasters such as cyclones and tsunamis. Waterlogging and soil salinity are serious threats to the sustainability of rainfed agriculture due to seawater inundation and intensive monsoon rainfall. Agroforestry land use systems have huge potential for sustainable agricultural production and livelihood security in these regions. 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 which are based on indigenous knowledge preserved through time immemorial. Plantation-based multi-storied integrated cropping systems, homegardens, farming in forests, fodder farming on neglected coconut plantations, multipurpose trees and shrubs on farmlands, site-specific systems for saline and waterlogged conditions, aquaculture in combination with forest and

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fruit trees or multi-enterprise agriculture or keeping mangroves intact, alley cropping, and mangrove plantations to protect coastlines are some prominent potential agroforestry systems which have been discussed in this chapter. Besides adopting these anecdotal and modern time-tested systems, modern technologies such as land shaping for multi-enterprise agriculture, domestication of halophytes in highly saline areas, alley cropping on sloping lands and site-specific research-oriented systems have great potential to address the current environmental challenges.

Keywords

Agroforestry systems · Alley cropping · Coastal areas · Homegardens · Mangroves · Multipurpose trees · Multi-storey cropping

13.1 Introduction

Humankind depends on the coastal ecosystems for its survival, with one-third of the world's population living in coastal areas that account for about four percent of Earth's total land area (UNEP 2006). Some important habitats in coastal zones include coral reefs, mangroves and salt marshes, estuaries and deltas. The coastal ecosystems provide a range of ecosystem services for environmental and livelihood security (UNEP 2006; UNEP-WCMC 2006). The coastal ecosystems provide essential services such as 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. People have been using the coast for millennia, and this constant use has changed it and the biodiversity found there. In recent decades, as the human population has grown, more and more people are living in coastal zones. As a result, human dependence on the coast has increased, and many fragile coastal habitats are under threat or are disappearing as a result of human activities. Rapidly increasing development has put numerous direct and indirect pressures on coastal ecosystems in the form of degradation and destruction. When these ecosystems are degraded, lost or converted, large amount of CO_2 is released into the atmosphere or ocean, accounting for up to 19% of global carbon emissions from deforestation (https://www.iucn.org/resources/issues-briefs/ocean-and-climate-change). Coral reefs and associated ecosystems are also regarded as one of the most stressed ecosystems globally and amongst the most vulnerable to climate change, which is threatening the goods and services they provide to millions of people. With increases in extreme weather events, sea-level rise, warming of the sea surface temperatures and ocean acidification, social, economic and environmental problems are being faced by the people living in coastal areas. The degradation of coastal ecosystems threatens the physical, economic and food security of coastal communities globally.

As of today, one of the potential threats to agriculture is the impact of climate change which is now a reality. As per NASA, 18 of the 19 warmest years have occurred since 2001, with the exception of 1998. The year 2016 ranks as the warmest on record. India, along with many developing countries, is one of the most vulnerable countries to climate change that is affecting agricultural production. Climate change can be expected to have varying effects on the expression of salinity, waterlogging, inundation in landscapes and soil erosion. The coastal areas are more vulnerable to the impacts of climate change because sea-level rise will add to the area under salinity and inundation. Over-exploitation of natural forests including mangroves, disposal of sewage and industrial effluents, oil spills, and defense and unlawful activities in oceans such as extraction of sea resources are also of great concern. Thus, hostile climate, frequent floods and cyclones, development of salinity due to seawater ingression and high water table rich in salts, severe soil erosion on hill slopes, silt deposition in the low-lying areas and faulty agricultural methods are some constraints in the agricultural development of these areas.

Adaptation of suitable agroforestry practices involving plantation crops, fruit and forest trees, spices, arable crops, forages, animals, poultry, honeybee and mushroom culture and fish and shrimp culture may play a vital role in increasing farm income and sustain livelihood and environmental security. Nair and Sreedharan (1986), Dagar (1995, 1996, 2000), Kumar et al. (2012), Dagar et al. (2014), Velmurugan et al. (2015, 2016) and Dagar and Minhas (2016) described many indigenous and research-oriented agroforestry systems of coastal and island regions. These studies show that most of the systems are site-specific with very few examples of their being extrapolatable. A vast majority of the virtues and benefits (except in research-oriented systems such as alley cropping) ascribed to them are anecdotal but time-tested. Rehabilitation of degraded mangrove areas and aquaculture retaining mangroves or behind mangroves will help in the protection of the coastline, improve ecological services and increase farm income. Mangroves are considered a great sink for carbon and play a vital role in environmental services including biodiversity conservation. Some of these aspects have been dealt with in this chapter.

13.2 The Extent of Coastal Regions and Drivers of Change

As per the Cambridge Advanced Learner's Dictionary & Thesaurus, a coastline is defined as "the particular shape of the coast, especially as seen from above, from the sea, or on a map". There are about 620,000 km of coastline in the world (www.worldatlas.com). Over one-third of the total human population (nearly 2.4 billion people) lives within 100 km of an oceanic coast, a fact emphasized by the devastating tsunami in the Indian Ocean in 2004. Greenland, an autonomous country located between the Arctic and the Atlantic Oceans, has one of the largest coastlines in the world with a total length of 44,087 km, while Monaco, a small European nation, has only 4.1 km of coastline, the smallest among the coastal nations of the world. Countries with the most coastline are shown in Fig. 13.1. An island is broadly defined as an area of land surrounded by a water body, such an ocean, sea, lake or river, and that is smaller than a continent. When there are several islands in the same geographical area, they are referred to as an archipelago. The largest island is Greenland Island with land area of about 2,166,086 km^2, located between the

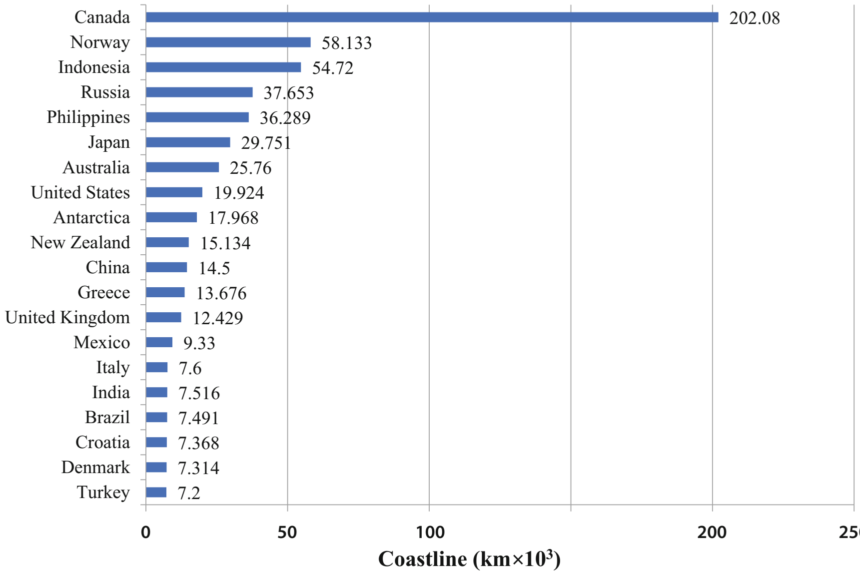

Fig. 13.1 Countries with the most coastline (km $\times$ 10^3) in the world (www.worldatlas.com)

North Atlantic Ocean and the Arctic Ocean, north-east of Canada (https://en.wikipedia.org/wiki/Geography_of_Greenland). Bishop Rock is the smallest island (1.57 ha) in the world located in the Atlantic Ocean; the island is popular for its well-built lighthouse. It has not been possible to come up with the total number of islands around other water bodies; there are around 2000 islands in oceans in the world.

India has a total coastline of 7516.6 km (India 2017) and is characterized by varied landforms and ecosystems. The mainland coastline consists of 5422.6 km and island territories 2094 km. Indian coastline touches nine states and four union territories. The nine states are Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha and West Bengal. Union territories include Daman and Diu, Puducherry, Andaman and Nicobar Islands and Lakshadweep Islands (Fig. 13.2). India's mainland coastline is divided into two parts: Eastern coastline and Western coastline. The Eastern coastline includes the Eastern Ghats and the Bay of Bengal and extends from Ganges Delta in the north to Kanyakumari in the south. Large parts of the coastal plains of India are covered by fertile soils on which different crops are grown. Rice is the main crop of these areas. The Western coastline, on the other hand, extends from Rann of Kachchh in the north to Kanyakumari in the south and is divided into three parts, Konkan coast, the Karnataka coast and Kerala coast. There are two groups of islands, i.e. Andaman and Nicobar Islands, spread over 8249 km^2 geographical area in the Bay of Bengal, and Lakshadweep Islands, spread over 32 km^2 area in the Arabian Sea.

The mangroves are found in the intertidal zones along the tropical coastlines, whereas the coral reefs are mainly found in the tropical and subtropical oceans. The coastal zone of India and that of Andaman and Nicobar Islands have the presence of extensive and diverse mangroves. These ecosystems are found along both the east

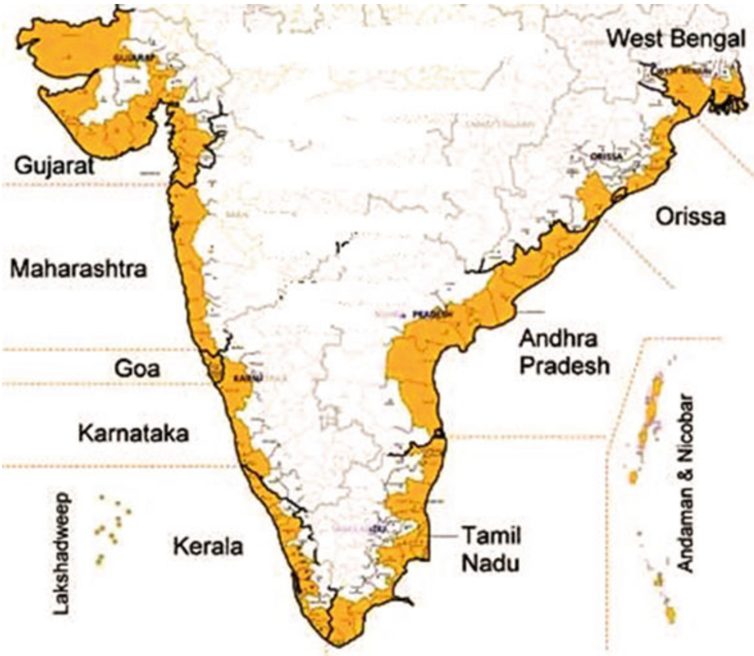

Fig. 13.2 Coastal and island regions (shaded) of India (not to the scale)

and west coasts of India. In India, important mangrove areas are in the Sundarban, Bhitarkanika, Krishna and Godavari delta of Andhra Pradesh, Andaman and Nicobar Islands, Gulf of Kuchchh, and the Pichavaram-Vedaranyam area of Tamil Nadu coast. The mainland coast of India has two widely separated areas containing reefs, i.e., the Gulf of Kuchchh in the northwest and Palk Bay and Gulf of Mannar in the southeast (Venkataraman 2011; Venkataraman et al. 2012). There are patches of reef growth on the West Coast, for example, coral reefs at Malvan. The Andaman and Nicobar Islands in the Bay of Bengal have fringing reefs around many islands and a long barrier reef (329 km) on the west coast. The Lakshadweep Islands in the Arabian Sea also have extensive reefs, but these are also poorly explored.

13.2.1 The Drivers of Change in Coastal Ecosystems

An array of anthropogenic and natural impacts has degraded, altered or eliminated coastal ecosystems; the drivers of change may have either direct or indirect impact upon ecosystems. The drivers of change in marine and coastal ecosystems based on UNEP report (UNEP 2006) are land use change and habitat loss, fisheries, invasive species, pollution, nutrient loading and climate change. Within the coastal population, 71% live within 50 km of estuaries, and in tropical regions, settlements are concentrated near mangroves and coral reefs. In particular, coastal habitats have been affected by land use change and habitat loss. Excessive amounts of sedimentation and agricultural practices upstream have resulted in the degradation of estuaries. Mangroves have been converted for various coastal zone development activities such as aquaculture and agriculture. Climate change is becoming the dominant driver of change, particularly in vulnerable habitats such as mangroves, coral reefs and coastal wetlands, which are especially at risk from resulting sea-level rises and temperature (UNEP 2006). Coral reefs are vulnerable due to coral bleaching (which sometimes causes coral mortality) and the spread of pathogens leading to the spread of coral diseases.

13.3 General Features of the Coastal Region of India

Large area of West Coast remains inundated by brackish water, while the East Coast suffers from water stagnation, floods and cyclones. These cyclones not only damage agricultural and domestic properties but also make the soil saline due to seawater ingression and high water table rich in salts. Ingress of seawater and silting of river beds, estuaries and creeks lead to the creation of marshy lands. Low-lying waterlogged marshy areas, flood plains and ill-drained lands are the common features in the coastal areas. All along the coastline, groundwater quality is being threatened due to the surface or sub-surface seawater intrusion. The areas affected by salinity and waterlogging are about 3 and 7 million ha, respectively (Table 13.1). The total area of groundwater within the depth of 3 m has been reported to be 7,016,000 ha, out of which 25.8% is the most critical (<2 m) for the pre-monsoon season (from 2003 to 2005). However, during the post-monsoon season, this area increased to 48.4% during the same period (RRSSC & CWC 2009).

Swamps and river banks are occupied by the mangrove and their associate halophytes. Indian mangroves are reported to cover 4921 km^2 area. Other natural vegetation includes evergreen, semievergreen and deciduous forests on hilly or uplands and grazing lands in pockets. Plantation crops integrated with livestock, poultry and rice fields along with aquaculture in back waters and homegardens are the main features.

Coastal and island regions fall mainly in five agroclimatic zones, which vary in rainfall, crops and soil (Table 13.2). They have wide variability in climate, topographical and edaphic conditions and support diverse cultivated crops as well as natural vegetation ranging from tropical rainforests to coastal mangroves. Dagar (1993), Dagar et al. (2014) and Dagar and Minhas (2016) have described the general features, natural vegetation and cropping systems of the island and coastal regions. These regions are bestowed with very rich biodiversity of both flora and fauna. The major cropping systems are based on coconut, areca nut, spices (black pepper, cardamom, clove), fruit trees, vegetables, pulses and paddy in low-lying areas.

Table 13.1 Extent of coastline, mangrove areas and saline and waterlogged soils of maritime states and union territories of India

State/union territory	Coastal length[a] (km)	Mangrove area[b] (000 ha)	Saline area[c] (000 ha)	Waterlogged area[d] (000 ha)
West coast regions				
Gujarat	1214.7	114.0	714	2602.3
Maharashtra	652.6	30.4	64	931.2
Karnataka	280.0	1.0	86	369.9
Kerala	569.7	0.9	26	116.4
Goa, Daman and Diu	160.5	2.9	18	5.3
Pondicherry	30.6	0.2	1	NA
East coast regions				
West Bengal	157.5	211.4	820	151.7
Orissa	476.4	24.3	400	754.7
Andhra Pradesh	973.7	40.4	276	1379.6
Tamil Nadu	906.9	4.9	100	704.7
Island regions				
Andaman and Nicobar	1962.0	61.7	15	NA
Lakshadweep	132.0	NA	NA	NA
Total	7516.6 (say 7517)	492.1	2520 + 492 = 3012	7015.8 (say 7016)

Source: [a]GOI (2017b), [b]FSI (2017); [c]Yadav et al. (1983), [d] RRSSC & CWC (2009); *NA* not available

13.4 Afforestation/Agroforestry Systems

Agroforestry systems (AFS) provide alternatives for restoring soil health and sustainable livelihood for the coastal population. Most of the systems and practices in coastal and island regions vary enormously in structural complexity and species diversity, their productive and protective attributes and socio-economic dimensions. These range from apparently "simple" forms of shifting cultivation and farming in forests to sophisticated hedgerow intercropping (alley cropping) systems and high-density multi-storey complex homegardens and from systems in which trees play a predominantly "service "role (e.g. shelter belts and windbreaks) to those in which they provide the main commercial products (e.g. intercropping with multi-storey plantation crops such as coffee, rubber, clove, cardamom, and pineapple). Multi-enterprise systems involving dairy animals, fish/shrimp culture, forest and fruit trees on dykes of ponds, plantations, animals, poultry, honeybee rearing, mushroom culture, vegetable and arable crops and forages give sustainable livelihood security.

The common denominator and scientific foundation of all these systems is the multipurpose trees (MPTs). The success of any system will depend upon the extent

Table 13.2 Salient agroclimatic features of coastal and island regions of India

Agroclimatic zone	States	Rainfall range (mm)	Climate	Main soil type	Main crops
Lower Gangetic plains	West Bengal	1302–1607	Moist subhumid to dry subhumid	Red and yellow deltaic, alluvium, red loam	Rice, jute, wheat, rapeseed
East coast plains and hill region	Orissa, Andhra Pradesh, Tamil Nadu, Pondicherry	780–1287	Semiarid to dry subhumid	Deltaic, alluvium, red loam, coastal alluvium	Rice, groundnut, ragi, pearl millet, pulses, sorghum, coconut
West coast plains and Ghat region	Tamil Nadu, Kerala, Goa, Karnataka, Maharashtra	2226–3640	Dry subhumid to per-humid	Laterite, red loam, coastal alluvium	Rice, groundnut, ragi, coconut, tapioca, coffee, spices
Gujarat plains and hill region	Gujarat	340–1793	Arid to dry subhumid	Deep black, coastal alluvium, medium	Rice, groundnut, cotton, pearl millet, black wheat, sorghum
Island regions	Andaman-Nicobar and Lakshadweep Islands	1500–3086	Humid	Coastal sandy and alluvium	Coconut, areca nut, rice, spices

to which the productive, protective, service potential and acceptability of MPTs is understood, exploited and realized through development and extension efforts (Nair and Dagar 1991; Dagar 2000). The number, type, distribution and uses of MPTs in agroforestry systems will entail several hundreds of species. Their uses and acceptability vary depending upon the size of landholding, growth performance in a region, cost of cultivation, household requirements, availability of market and getting the reasonable price of the products. After a comprehensive survey of the coastal and island regions and perusal of literature, Dagar (1991, 1995, 2000) prepared a list of MPTs along with their main uses, mode of propagation and features of special interest (Table 13.3). Besides these, Ragavan et al. (2019) have reported 46 true mangrove species (42 species and 4 natural hybrids) along eastern and western coasts, estuaries, along back waters and island coasts. Overall, the mainland has 40 mangrove species (all found on the eastern coast and only 27 of these on the western coast), and 38 species are found in Andaman-Nicobar Islands. Dagar (1982, 2003) listed 188 species of mangrove associates, including climbers, epiphytes and semiparasites which contribute significantly to the vegetation structure of mangrove habitats. Ragavan et al. (2019) listed more than 100 important associate species of Indian mangroves. For the rehabilitation of degraded mangrove habitats, all these

Table 13.3 Characteristics of multipurpose trees and shrubs commonly found in agroforestry systems of coastal and island regions of India

Species	Main distribution			Major uses	Other uses	Mode of propagation	Remarks
	East coast	West coast	Islands				
Acacia aneura	+	–	–	1,3,5,6,7	ta	s	co, fg
A. auriculiformis	+	+	+	1,3,5,6,7	ta	s, t	co, fg, dt
A. leucophloea	+	+	–	1,3,5,6,7	ta, ch	s, t	co, fg, dt
A. mangium	+	+	–	1,3,5,6,7	ta, ch		co,fg
A. nilotica	+	+	–	1,3,5,6,7	ta, ch	s, t	co, fg, dt
Achras zapota	+	+	+	2,3		g, t	Fruit, dt
Aegle marmelos	+	+	–	1,2,3,7	fr, b, m	s, su	co, dt
Ailanthus excelsa, *A. grandis*	+	+	–	1,3,6,7	ta, p	s, t	co, fg, mu
Albizia amara, *A. chinensis*, *A. falcataria*, *A. lebbeck*	+	+	–	1,3,4,5,6,7	ta	s, t	co, fg, mu
Amoora rohituka	+	+	+	3,5,6,7	ta, m, canoes	s, t	co
Anacardium occidentale	+	+	+	3,4	m, o, n	s, t, g	co, coastal
Annona squamosa, *A. muricata*	+	+	+	2,3	fr, b	s, t, g	co
Anogeissus latifolia	+	+	+	3,6,7	ch, re, m	t	co
Areca catechu, *A. triandra*	–	+	+	2,3	n, th, cs, po	t	fg
Artocarpus chaplasha, *A. gomeziana*, *A. heterophyllus*, *A. incisa*, *A. lakoocha*	+	+	+	1,2,3,7	v, fr, csh	t, c, g	Large tree, fruits on stem
Azadirachta indica	+	+	–	1,2,3,4,6,7	m, o, t, ir	s, t	co, shade
Bambusa arundinacea, B. nutans, other spp.	+	+	+	1,3,4,6,7	th, p, po, lf, cs	su, c	co, fg, dt
Bauhinia acuminata, *B. racemosa*, *B. variegata*	+	+	–	1,2,3,5,6,7	v (flower buds)	s, t	co
Bischofia javanica	+	–	+	3,6,7	csh, ta, o, m	s, c, su, t	co, fg
Bombax malabarica	+	+	+	1,3,4,6	fi, cs, csh	t	fg, fruit yield fibre
Borassus flabellifer	+	+	–	1,2,3,4,6	b, th, sugar, fr	t, s	Palm

(continued)

Table 13.3 (continued)

Species	Main distribution			Major uses	Other uses	Mode of propagation	Remarks
	East coast	West coast	Islands				
Carica papaya	+	+	+	2	fr,m,v	t, s	Weak stemed
Carissa carandas, *C. inermis*	–	+	+	1,2,3	fr (pickle) ih, m, sw	c	sh, co
Cassia siamea	+	+	+	1,3,5,6	a, lf, ta, mu	t, s, c	co,
Casuarina equisetifolia, *E. glauca*	+	+	+	3,4,5,6,7	p, po, re, ta, sp	t, s, su	fg, co, windbreak
Ceiba pentandra	+	+	+	1,3,4,6	fi, lf, cs, csh	t	fg, fruit fibre
Cinnamomum zeylanica	–	+	+	2,3,4	m, bark spice	t	Shrub
Citrus aurantifolia, *C. limon*, *C. maxima*, *C. medica*	+	+	+	2,3,4	b, fr	t, g, c	Small tree
Cocos nucifera	+	+	+	2,3,4,6	n, o, b, th, m	t	Palm
Coffea arabica, *C. cenephora*	–	+	+	2,3,4	b	t, c	Shrub, coffee beans
Cordia grandis, *C. myxa*, *C. rothii*	+	+	–	1,2,3,6,7	fr (pickle), m, v, gum	s, c, t	co, fg
Dalbergia latifolia, *D. sissoo*	+	+	–	1,2,3,5,6,7	i, csh	t, s, su, c	co
Elaeis guineensis	–	+	+	2,4	o, b, th, feed	t	Red oil palm, co
Emblica officinalis	+	+	+	1,2,3,4,6,7	fr, pickle, o, ch, p, ta, m	t, s, c	frt rich in vit c
Erythrina fusca, *E. indica*, *E. variegata*	–	+	+	1,3,5,6,7	lf, csh, cs, fi	s, t, c	co
Eucalyptus camaldulensis, *E. tereticornis*	+	+	–	3,4,7	l, po, p, r, o	t	co
Ficus gibbosa, *F. hispida*, *F. relegiosa*, *F. rumphii*	+	+	+	1,3	sp, m	s, c	co
Garcinia cowa, *G. microstigma*	–	+	+	1,2,3,4, 6,7	sp, v (young leaves), m, frt (juice)	t, st	Small fruit tree
Gliricidia sepium	–	+	+	1,3,5,6	a, gm, cs, lf, mu	c, t	Shrub, fg, co
Gmelina arborea	–	+	+	1,3,7	h, p, su	s, t	co, fg

Hevea brasiliensis	–	+	+	3,4	csh	t	rubber
Hibiscus tiliaceus	+	+	+	1,3,6	sch, po, sp., fi (bark)	s, c, t	coastal, co
Jatropha curcas, *J. gossipifolia*	+	+	+	4,3	lf, m, bio-diesel	c, s	co
Leucaena leucocephala	+	+	+	1,3,5,6	a, lh, gu, m, gm	s, c, t	sh, cp, fg
Mangifera indica	+	+	+	1,2,3,4.7	b, fr, pickle	s, t, g	Large tree
Morinda citrifolia	–	+	+	1,3,6.7	fr, pickle, juice, m, v (leaves), sp	s, t	co, sw
Moringa oleifera	+	+	+	1,2,3	v, m, pu, o, all parts used as veg	t, g, c, s	co, fg, rich in minerals
Morus alba	+	+	+	1,2,3,4	fr, sw, pu, twigs for basket-making	s, c, g, t	sh, co
Murraya koengii, *M. paniculata*	–	+	+	2,3	b, m, lf, lh, spice	t, c, s	co, shrub
Musa paradisiaca	+	+	+	1,2.4	fr, v, m	c, t, su	Shrub with pseudostem
Myristica andamanica, *M. fragrans*	–	+	+	2,3,4	mace (spice), m, religious ceremonies	s, t, g	Commercial importance
Pandanus fascicularis, *P. leram*, *P. tectorius*	+	+	+	2,4,6	fr, v, th, sp., fi, o, m	c, su, s	Coastal, co, fragrance oil
Pithecellobium dulce	+	+	+	1,2,3,4,5,6,7	lh, lf, ta, m, fr	c, t, s	co
Pongamia pinnata	+	+	+	1,3,4,5,6,7	fi, m, o, ir, sp., gm	c, t, su	co, biodiesel
Psidium guajava	+	+	+	2,3	fr, m, juice	g, t, su	co, frt rich in vit c and minerals
Punica granatum	+	+	+	2,3	fr, m, spice (seed)	t	Small tree
Salvadora persica	–	+	–	1,2,3,4	frt oil, m, sp	t, s	co, also littoral
Sapindus trifoliatus	–	+	+	3,4	soap, m	s, t	small tree
Sesbania grandiflora, *S. javanica*	–	+	+	1,2,3,5,6	v, ch, fi, ta	s, t	fg, co
Syzygium aromaticum	–	+	+	2,4,7	spice, o, m	t	Shrub, clove

(continued)

Table 13.3 (continued)

Species	Main distribution			Major uses	Other uses	Mode of propagation	Remarks
	East coast	West coast	Islands				
Syzygium cuminii	+	+	+	1,2,3,6,7	fr, ta, d, o, m	t, c	co, fruit nutritive and medicinal
Tamarindus indica	+	+	+	1,2,3,4,5,6,7	fr (pulp), b, csh, d, ta, h	t, c, s	co, fruit in *chuttnies*
Tectona grandis	+	+	+	3,6,7	l, d, oxalic acid	t	Timber tree
Terminalia catappa	+	+	+	1,2,3.6,7	sp, pu, kernel oil, d, sw, m, o	t, s	Oil like almond oil
Theobroma cacao	–	+	+	1,2,3,4	b(cocao), m, o	t	Cocoa from beans
Thespesia populnea	+	+	+	1,3,6,7	po, sp., fi (bark), d, m, o	c, s	co, coastal
Trema tomentosa, *T. orientalis*	–	+	+	1,2.6,7	fr, ta, m leaf forage	c, t	fg, co
Vitex negundo, *V. trifoliata*	+	+	+	3,6	lh, lf, m, sp	c	sh, fg, co
Ziziphus mauritiana	+	–	–	1,2,3,6,7	fr, lf, sw, m	t, g	co

Source: Dagar (1995, 2000)
Major uses: Numbers 1–7; 1 = fodder, 2 = food (vegetables, fruits), 3 = fuel, 4 = industrial uses, 5 = nitrogen fixing, 6 = soil amelioration, conservation, shelter belt, 7 = timber
Mode of propagation: c = cutting, g = grafting, s = seed, su = suckers, t = transplanting
Other uses: a = alley crop, b = beverage, ch = charcoal, cs = crop support, csh = crop shade, d = dye, fi = fibre, fr = fruit, gm = green manure, gu = gum, h = honeybee forage, ir = insect repellent, l = lumber, lf = live fence, lh = live hedge, m = medicine, mu = mulch, n = nuts, o = oil, p = pulp, po = pole, re = resin, sp = sea shore protection, sw = silk worm food, ta = tannin, th = thatching, v = vegetables
Remarks: co = coppices well, fg = fast growing, li = littoral, sh = shrub, dt = drought tolerant

species [which besides coastline protection also have many other uses (firewood, timber, forage, honeybee nets, medicine, tannin, etc.) including environmental services] have a significant role to play. All along protected coasts, suitable mangrove and their associate species (from Table 13.3) may be grown successfully both in isolation and associated with aquaculture.

Many MPTs are being improved in many institutes and domesticated for their multipurpose use. For example, during last one decade, *noni* (*Morinda citrifolia*) has been widely collected and cultivated as a sole tree and also in combination with several plantations such as coconut, cashew and fruit trees in Andamans. Farmers have been trained to utilize its fruit as raw, pickle and juice and jellies and now has become a tree of every household (Singh et al. 2009). The Bay Islands are blessed with several trees in natural stands with several varieties, which may be domesticated for high-value crops, collected and grown for improving their germplasm. For example, several varieties/ecotypes of nutmeg (*Myristica fragrans*), *Rudraksha* (*Elaeocarpus sphaericus*), betel vine (*Piper betle*), banana, mango and many others are found distributed wild in natural forests in coastal and island regions. The tropical evergreen forests of islands are blessed with a variety of orchids, which must be protected in situ, and some of these must be collected and multiplied, and the possibility of commercial exploitation of selected species must be explored. For that reason, institutes like Botanical Survey of India and Central Island Agricultural Research Institute of Port Blair must collaborate and develop a viable program.

Some of the important traditional and site-specific agroforestry systems/practices being followed or have been tested in islands and coastal areas are described below:

13.4.1 Farming in Partially Felled Forests and Cultivation of Commercial Crops Under the Shade of Natural Forests

Growing of commercial crops under the shade of trees of natural forests in Western Ghats of peninsular India is very common practice. For example, small cardamom (*Elettaria cardamomum*) is grown as a traditional commercial crop under trees in Cardamom Hill Reserve (CHR) in the high-altitude regions of Kerala. Dominant trees in the evergreen or semievergreen natural forests are retained by the growers in this age-old cultural system. Kumar et al. (1995) studied the floristic diversity of four CHR sites. *Vernonia arborea*, *Artocarpus heterophyllus*, *Actinodaphne malabarica*, *Persea macranth*a and *Erythrina lithosperma* were reported to be common shade trees in Pampadumpara stands of natural forests, which possess 522 trees per ha. 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*. 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* were important tree species found in evergreen natural forests. The 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, 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.

In one study, Kumar et al. (2001a, b) recorded the highest rhizome yield (5.0 Mg ha^{-1}) of ginger under 3 years old *Ailanthus* trees at a density of 2500 trees per ha, and the yield was optimum for below 5 years old stands on good sites. It varied under different stocking rate. The rhizome yield was 3.7, 3.6, 4.0 and 3.5 Mg ha^{-1} in the 3333, 1660, 1111 trees per ha stocking level and control (without trees), respectively.

In another study, Kunhamu et al. (2008) observed that the removal of two-third of 8-year-old *Acacia mangium* trees promoted understorey ginger productivity with a yield of 787 kg ha^{-1} as compared to 439 kg ha^{-1} under un-thinned tree stand (1600 trees ha^{-1}), while 2473 kg ha^{-1} ginger was produced without any tree. However, the net present value in INR was obtained highest in *A. mangium* + ginger (INR 481,772; BC ratio 4.26) un-thinned stand followed by one-third removed (1066 trees per ha), 50% removed (800 trees per ha) and two-thirds removed (533 trees per ha), respectively, while from sole ginger only INR 158,488 could be obtained showing that agroforestry system is more sustainable and remunerative.

Most of the settler farmers in Andaman-Nicobar Islands (ANI) are allotted about 4 ha land; half of it is low-lying paddy land and the remaining hilly forest land from where commercially timber trees have been extracted. These partially felled areas and similar other forest lands, especially those which are encroached (a recent phenomenon), are underutilized as they support obnoxious weeds such as *Chromolaena (Eupatorium) odorata*, *Mikania cordata*, *Hyptis capitata* and *Melastoma malabathricum*. Impeded regeneration and land deterioration by accelerated erosion are evident. Farming in such holdings (farming in forest) is very appropriate. The young vigorous forest trees can be retained at regular intervals after clearing weeds and wild bushes and pruning of lower branches to create clean open spaces for growing partially shade-tolerant shrub and herbaceous species. Some new seedlings of appropriate multipurpose trees (MPTs) may be planted in wider spaces in tree rows (for a list of MPTs, see Table 13.3). *Morinda citrifolia* has been widely explored for various purposes in islands. *Ardisia solanacea*, *Ceiba pentandra*, *Sesbania grandiflora*, *Gliricidia sepium, Casuarina equisetifolia, Moringa oleifera*, and many species of banana (*Musa acuminata*, *M. textilis, M. paradisiaca*) are commonly grown with success.

The Jirkatang Farm owned by the Department of Agriculture in South Andaman is a unique example of this type of farming system. Tall forest trees including commercial timber trees such as *Dipterocarpus* spp., *Terminalia* spp., *Bombax* *insignis*, *Lagerstroemia hypoleuca*, *Artocarpus chaplasha*, *Albizia lebbeck* and *Cannarium euphyllum* have been retained as the canopy of top-most storey. The spices such as cinnamon (*Cinnamomum zeylanicum*) and clove (*Syzygium aromaticum*) are grown as middle storey. Some trees such as *Ceiba pentandra*, *Moringa oleifera*, *Artocarpus* spp. and *Mangifera indica* are also part of middle storey. Pineapple is cultivated along slopes in the light zone along with some grasses or shade-tolerant crops as ground storey crops. Climbers like black pepper (*Piper nigrum*) and betel vine (*Piper betle*) planted near trees get needed support. Areca nut is ideal support for these climbers.

Coconut (*Cocos nucifera*), red oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) have been found suitable plantations for Andamans though cultivation of red-oil palm as monoculture plantation is discouraged based on ecological reasons as it has been found deteriorating the soil fertility after 13 years of plantation of sole oil palm (Dagar et al. 1995). Nutmeg (*Myristica fragrans*), coffee (*Coffea indica/ C. arabica*) and spices like clove and cinnamon can be planted between trees as middle storey crops. Kapok (*Ceiba pentandra*), areca nut, sticks of *Gliricidia* and *Erythrina* are used as support for black pepper and betel vine. Partial shade-tolerant crops such as turmeric (*Curcuma domestica*), ginger (*Zingiber officinale*), taro (*Colocasia esculenta*) and Jamicand (*Dioscorea alata*) may find space as intercrops in plantation-based systems. Other crops such as vegetables (cucurbits, okra, gourds, etc.) or exotic fodder species such as *Andropogon gayanus*, Para grass (*Brachiaria mutica*), Congo signal (*B. ruziziensis*), Blue panic (*Panicum antidotale*), Gatton panic (var of *P. maximum*), Kazungula (*Setaria anceps*), hybrid napier (*Pennisetum purpureum*), thin napier (*P. polystachion*), Guatemala grass (*Trepsicum laxum*), guinea grass (cvr of *Panicum maximum*) and legume-fodders like stylo (*Stylosanthese guianensis*, *S. humilis*, *S. hamata*), calopo (*Calopogonium mucunoides*), cordofan pea (*Clitoria ternatea*), and siratro (*Macroptilium/Phaseolus atropurpureum*) and industrial aromatic grasses such as lemon grass (*Cymbopogon flexuosus*) have been found doing well on sloping land in islands (Sharma et al. 1990, 1991; Dagar 1995; Dagar and Singh 1999). These provide fodder and check soil erosion on sloping land. Nutritional capabilities of some fodder trees, grasses and legumes suitable for islands have been tabulated by Sharma et al. (1990, 1992) and Dagar and Singh (1999). Multitier cropping system model comprising coconut (*Cocos nucifera*) + black pepper (*Piper nigrum*) + ginger (*Zingiber officinale*) + banana (*Musa* sp.) in the experimental block of AICRP on Palms, Sippighat Farm, South Andaman, is shown in Figs. 13.3 and 13.4.

13.4.2 Plantation-Based Multi-Storey Cropping Systems and Homegardens

Multi-storey cropping systems (MSCS) also known as forest gardens or homesteads and homegardens are the most important form of land use in the tropical world. Tropical humid monsoon climate of ANI and tropical savannah climate of Lakshadweep Islands (LDI) have such AFS. The multi-storey stand structure of

Fig. 13.3 Multitier cropping system model comprising coconut (*Cocos nucifera*) + black pepper (*Piper nigrum*) + ginger (*Zingiber officinale*) + banana (*Musa* sp.) in the experimental block of AICRP on Palms, Sippighat Farm, South Andaman (Photo credit: Dr. Ajit A. Waman)

Fig. 13.4 Coconut-based cropping system model with coconut (*Cocos nucifera*) + pineapple (*Ananas comosus*) + ginger (*Zingiber officinale*) in the experimental block of AICRP on Palms, Sippighat Farm, South Andaman (Photo credit: Dr. Ajit A. Waman)

MSCS has its origin in tropical rain forests and is known to exist since 13,000–9000 BC among the fishing communities of tropical forests (Wiersum 2004). There is long history of homegardens in coastal areas of India. The travelogue of the Persian traveler Ibn Battuta (1325–1354) mentioned that in the densely populated and intensively cultivated landscapes of Malabar Coast, coconut and black pepper were prominent along the houses (Randhawa 1980). The writings of the colonial period (Mateer 1883; Logan 1906; Nagam 1906) provide evidences of home gardening in India.

Homegarden in addition to plantation and fruit trees includes poultry, livestock and fish pond. These components being an integral part of the homegarden function in an interactive manner. Because of their multi-commodity structure, these offer food and nutritional security to the subsistence farmers, 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 et al. 2014). The homegarden farmers are perpetual experimenters and are constantly trying and testing new species and varieties and their management (Kumar and Nair 2004), and their success is time-tested as over centuries farmers have selected specific species and manipulated their physical and ecological locations in homegardens planting for maximizing space and production. The crop combinations found in the homegardens of a region, however, are strongly influenced by the biophysical and sociocultural factors besides the specific needs and preferences of the household and nutritional complementarities with other major food sources. As a consequence, homegardens vary greatly in species, species richness, structural complexity and size, but general principles are broadly similar (Gillespie et al. 1993). From the ground layer to the upper canopy, the gradient of light and humidity determine different niches that species exploit according to their own requirements. The position, height and shade tolerance of plants are important traits that are acquired with time. Therefore, a study of these parameters gives an idea of the temporal and spatial positioning of plants, species interaction and mixed species silviculture that are pertinent for designing a multistratal agroforestry and management of its productivity (Gillespie et al. 1993). In India, the homegardens of Kerala and Bay 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 multistorey cropping system, thereby efficiently harnessing solar radiation and using soil moisture and nutrients.

Contrary to the popular belief, a sizeable percentage of the total production of most plantation crops in developing countries like India comes from small holdings and for these multiple cropping systems is of great importance and relevance. Coconut, areca nut, coffee, rubber, oil palm and cashew are main plantation crops in coastal and island regions. Among fruits, banana, papaya, mango, guava, pineapple, sapota, lemon, lime, mandarin, jackfruit and custard apple are 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.

As per statistics of the agricultural department, Agricultural Statistics at a Glance 2017 (GOI 2017a), coconut is cultivated on 2.1 million ha area, out of which 84% area is cultivated by Kerala, Karnataka and Tamil Nadu, with 86.6% total yield of the country (Table 13.4); however, per unit area yield is highest in Andhra Pradesh (9451 kg ha^{-1}). According to Coconut Development Board of India, in 2017–2018, Kerala and Tamil Nadu produced 14,472.5 million nuts (60.8% of total 23,798.23 million nuts) with an average of 12,055 nuts per ha. In the country, about one million ha area is under cashew (mainly in Maharashtra, Andhra, Orissa, Karnataka and Kerala), 316.6 thousand ha is under oil palm, 474 thousand ha under areca nut, and 841 thousand ha under banana cultivation. Major oil palm production is in Andhra Pradesh (1148 thousand Mg, 88.5% of total production). According to Coffee Board's data, total coffee exports rose to $958.80 million in 2017 from $818.65 million in 2016 (www.business-standard.com). During 2018–2019, India exported 328,800 Mg of coffee, and in 2017–2018 a total of 84,300 Mg worth INR 51.69 billion cashew kernels. The rubber cultivation reached to 0.59 million ha in 2003–2004 with a production of 218.7 thousand Mg worth INR 12,900 million. Thus, plantation crops have a tremendous potential in coastal and island regions. These along with many tropical fruit trees and MPTs constitute multi-storey agro-forestry systems.

MSCS of islands are built around coconut and areca nut (ANI) and coconut (LDI), and these trees function as a fulcrum for a wheel. When farmer resides in the MSCS farm, they may be termed as homesteads or homegardens (HGs), and in both the groups of islands, the majority of the MSCS are HGs. In Andamans, both areca nut- and coconut-based multi-tiered systems are most frequent where black pepper is trained on the trunks of coconut and areca nut (Fig. 13.3) and spices are grown as middle storey crops and vegetables or tuber crops as well as forages as intercrops.

Fodder grasses are commonly harvested from the coconut stands. The presence of farm family (dwelling) in the farm daily throughout the year brings in a whole lot of changes in the crops grown (more fruits and vegetables, forages) and enterprise mix (integrated with back yard poultry, livestock, fish) and thus have wide diversity than MSCS. In Nicobars, we also come across the natural stands of coconut, and sometimes, the natives also grow vegetables and pineapple (Fig. 13.5) in these stands. In Sunderbans of West Bengal, farmers cultivate vegetables on dykes of fish ponds (Fig. 13.6).

During the last two decades, several attempts have been made in the cropping system research to include aromatic and medicinal plants with the conventional food, commercial and plantation (including MPTs) crops. This increased not only the land use efficiency and productivity but also the net returns from the particular piece of land (Maiti and Raju 2004). Mixed cropping, alley cropping and multitier cropping with these plants proved to be quite successful with increased nutrient recycling having reduced pest and disease load on the crops. Among important medicinal and aromatic species suitable for coastal ecosystem include *Abelmoschus moschatus*, *Acorus calamus*, *Adhatoda vasica*, *Aloe barbadensis/vera*, *Alpinia galanga*, *Andrographis paniculata*, *Asparagus racemosus*, *Bacopa monnieri*, *Cassia angustifolia*, *Catharanthus roseus*, *Centella asiatica*, *Clitoria ternatea*, *Coleus forskohlii*, *Curculigo orchioides*, *Curcuma longa/domestica*, *C. aromatica*, *Cymbopogon flexuosus*, *C. martini*, *Gloriosa superba*, *Kaempferia galangal*, *K. rotunda*, *Mucuna pruriens*, *Piper longum*, *Plumbago zeylanica*, *Pogostemon*

Table 13.4 Area, production and yield status of important plantation and other tropical important crops grown in coastal and island regions (based on year 2015–2016)

States/UT	Area (000 ha)	Area % of all country	Production (000 Mg)	Production % of all country	Yield (kg ha^{-1})
Coconut					
Kerala	770.62	36.9	5113.14	33.5	6635
Karnataka	526.38	25.2	3529.83	23.1	6706
Tamil Nadu	459.74	22.0	4247.12	27.8	9238
Andhra Pradesh	103.95	5.0	982.42	6.4	9451
West Bengal	29.51	1.4	257.11	1.7	8712
Orissa	50.91	2.4	226.00	1.5	4440
Gujarat	22.81	1.1	215.20	1.4	9433
Maharashtra	27.75	1.3	186.67	1.2	6728
Others	96.81	4.6	498.84	3.2	5153
All India	2088.47	100.00[a]	15256.33	100.0[a]	7305
Cashew					
Maharashtra	186.20	18.0	220.0	32.8	1200
Andhra Pradesh	185.57	17.9	95.5	14.2	490
Orissa	182.91	17.7	80.5	12.0	430
Karnataka	125.86	12.2	73.0	10.9	572
Kerala	87.01	8.4	72.0	10.7	851
Tamil Nadu	141.33	13.7	58.0	8.7	400
Goa	58.17	5.6	28.0	4.2	450
Others	67.30	6.5	43.3	6.5	643
All India	1034.36	100.0	670.3	100.0	650
Red oil palm[b]					
Andhra Pradesh	156.53	49.4	1147.78	88.5	NA
Karnataka	42.40	13.4	14.74	1.1	NA
Tamil Nadu	30.31	9.6	7.81	0.5	NA
Gujarat	5.72	1.8	0.52	0.05	NA
Orissa	20.77	6.6	4.57	0.3	NA
Goa	0.95	0.3	3.22	0.2	NA
Kerala	5.78	1.8	40.61	3.1	NA
Telangana	16.90	5.3	75.45	5.8	NA
Maharashtra	1.47	0.5	NA	0.05	NA
Andaman-Nicobar Island	1.59	0.5	NA	NA	NA
Others (mainly NEH)	34.18	10.8	3.78	0.3	NA
All India	316.60	100.0	1298.48	100.0	NA
Areca nut					
All India	474.36	–	713.84	–	1505
Banana					
All India	841.19	–	29134.82	–	34,635

(continued)

Table 13.4 (continued)

States/UT	Area (000 ha)	Area % of all country	Production (000 Mg)	Production % of all country	Yield (kg ha^{-1})
Cardamon					
All India	85.66	–	24.07	–	281
Pepper					
All India	128.59	–	54.64	–	425
Tapioca					
All India	203.50	–	4344.16	–	21,347

Source: Agricultural Statistics at a Glance (GOI 2017a, b)
[a]Due to adjustment of decimals, the total may not be exact 100.0
[b]Area under red oil palm is the total cultivated area up to March 2017

Fig. 13.5 Annuals and pineapple are grown in the interspaces of natural coconut in Car Nicobar Island (Source: Velmurugan et al. (2016))

Fig. 13.6 Typical view of homestead lands in coastal Sundarban, India

cablin, *Sida cordifolia*, *Solanum surattense*, *Tinospora cordifolia*, *Tribulus terrestris* and *Zingiber officinale*.

Most of the homegardens in Kerala and Andaman-Nicobar Islands are rich in species composition and productivity. These have been worked out by many (Nair and Sreedharan 1986; Ismail 1986; Jose 1992; Kumar et al. 1994; Dagar 1995; Pandey et al. 2007; Dagar et al. 2014) and are described below:

13.4.2.1 Species Composition and Structure

In earlier studies of homegardens, there was a listing of species, but there was no quantitative information. Jose (1992), however, calculated Simpson's diversity indices for different size-class categories and components and analysed 80 households and concluded that the introduction of rubber (*Hevea brasiliensis*) into the homegardens resulted in a reduction of species diversity. 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 homegardens of Kerala. They found tremendous variability in both the number of trees and shrubs present and species diversity of the selected homesteads in different provinces. The small (<2 ha), medium (2–5 ha) and large (>5 ha) sized holdings also exhibited profound variability in the number of woody taxa and the individuals present. In total, 127 woody species (girth at breast height > 15 cm) were encountered. The mean number of woody taxa found in homegardens 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 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.

Kumar et al. (1994) reported that the farmers tend to prefer timber trees such as *Ailanthus triphysa* (highest frequency), teak (*Tectona grandis*), *Erythrina indica* and *Bombax ceiba* besides fruit trees such as mango (*Mangifera indica*), jack (*Artocarpus heterophyllus, A. hirsutus*), cashew (*Anacardium occidentale*), tamarind (*Tamarindus indica*), guava (*Psidium guajava*) and gooseberry (*Emblica officinalis*). Among other MPTs, *Macaranga peltata*, *Thespesia populnea*, *Gliricidia sepium*, *Swietenia macrophylla*, *Casuarina equisetifolia*, *Delonix regia*, *Leucaena leucocephala*, *Azadirachta indica*, *Ceiba pentandra*, *Annona squamosa*, *Syzygium cuminii* and *Dalbergia latifolia* are important. Standing stock of timber and firewood ranged from 6.6 to 50.8 m^3 ha^{-1} (average 25 m^3 ha^{-1}) and from 23 to 86 m^3 ha^{-1} (average 50 m^3 ha^{-1}), respectively. From these observations, it was evident that both naturally occurring wild plants and deliberately introduced plants occur in the homegardens. New species may be introduced exclusively based on their utility in terms of food, vegetables, medicine, timber, ornamental, religious, etc.

Results from a 430-HG survey across ANI (Pandey et al. 2007) indicated that mean size of Andaman's HGs (0.05–2.0 ha) is smaller than Nicobar (0.5–5.0 ha) but for species diversity, former was three times (33–34 species) richer than the later (9–12 species). Based on operational holding data (year 2010–2011) of LDI, 88.35%

and 10.06% of total 10,285 holdings were marginal (<0.5 ha) and small farmers (0.5–2.0 ha) who operated 43.26% and 32.2% of total farm area (2750 ha), and thus, HGs of LDI are smaller in size than the Nicobar HGs. Pandey et al. (2007) reported that 34 woody plant species are found in the homegardens of Andaman and 12 in Nicobar that are planted, cared and harvested. These are classified as palms, fruit trees, spice trees and agroforestry/forestry trees. Though the species are common, their density varies within and among the sites. Areca nut is dominant in the homegardens invariably in all the islands of Andaman. However, coconut dominates in the homegardens of Nicobar. Dominance of most of the fruit and spice trees is higher in Andaman compared to that in Nicobar's homegardens. Among the Andaman groups of islands, almost all the fruit trees found are encountered in the homegardens, but their proportions differ. Forest trees are found in almost all the homegardens of the studied islands, but their numbers are higher in Andaman compared to that found in Nicobar group of islands.

Dagar (1995) and Pandey et al. (2007) studied the homegardens of Andamans. It was found that cow is the major animal of livestock (1–6 per homegarden, averaging 2 cows) and kept in about 60% homesteads. Many keep goats also. Livestock feeding totally depends on grazing. Cows are trained in such a way that they go for grazing in the morning in a nearby forest after milking and comeback in the evening almost at the same time. In Andamans, on an average, one poultry shade is found in the 80% homegardens. Poultry birds are composed of hen, cock and duck and the hen ranging from 2 to 55 (average 13 birds) per homegarden. On an average, 2340 eggs are produced by a single hen and 633 eggs by ducks in a year for each homegarden. Nearly 25% of the total eggs are consumed by households, whereas 75% are sold. Though ducks produce a relatively greater number of eggs and the cost of eggs is also high, the numbers of ducks are lower because all farmers do not own a pond. All the poultry birds feed among the trees in homegarden. Rice fields are located quite close to coconut-areca nut orchards in the Andamans. Smallholders grow mostly long-duration (6 months) rice to be harvested in December. Generally, between the two rice crops, they grow vegetables in the rice fields. Though the vegetable crops are common among the islands, their proportions as well as acreages vary. The proportion of tomato, brinjal and chilly is always higher in Little Andaman than that in any other islands. However, the proportion of cucumbers, gourds, cowpea, okra and amaranths is nearly equal among the islands. Maximum 0.5–2 ha per household are cultivated for vegetables in Middle Andaman followed by 0.25–1 ha per household in North Andaman. Acreages of vegetable cultivation are the lowest 0.02–0.25 ha per household in South Andaman. Cole crops are grown from November to January, whereas the remaining crops are grown round the year. Nicobarese in Nicobar do not know vegetable and rice crop husbandry. Paddy cultivation in Nancowry is similar to that in the Andamans, but the vegetable cultivation is negligible.

In Andaman and Nicobar Islands, Dagar (1995) reported 66 species commonly grown in homegardens categorized as vegetables (29 species), fruits (16), pulses (6), nuts/oils (7), spices and condiments (6) and others (2). The average yield of economic product of these commodities was also reported (Table 13.5). Jacob

Table 13.5 Yield of some fruit and vegetable species grown with plantations in Andaman Islands

	Vernacular name	Economic produce	Average yield
Vegetables			
Abelmoschus esculentus	Okra, ladies' finger	Fruit	8–10 Mg ha^{-1}
Amaranthus gracilis, *A. blitum var oleracea*	Amaranthus, chulai	Entire plant	10–15 Mg ha^{-1}
Artocarpus spp.	Jack fruit	Fruit	250–300 fruits (each 2–5 kg) $tree^{-1}$ $year^{-1}$
Basella rubra	Poi	leaves	15–20 Mg ha^{-1}
Capsicum annuum, *C. frutescens*	Green pepper	Fruit	20–25 Mg ha^{-1}
Carica papaya	Papaya	Fruit	13–15 Mg ha^{-1}
Colocasia esculenta	Taro, arvi	Rhizome	8–12 Mg ha^{-1}
Cucurbita maxima, *C. pepo*, *C. moschata*	Pumpkins	Fruit	20–25 Mg ha^{-1}
Dioscorea spp.	Dioscorea	Tuber	20–25 Mg ha^{-1}
Eryngium foetidum	Burmese coriander	Leaves	7–10 Mg ha^{-1}
Ipomoea batatas	Sweet potato	Root	30–35 Mg ha^{-1}
Lagenaria vulgaris	Bottle gourd	Fruit	35–40 Mg ha^{-1}
Luffa acutangula, *L. cylindrica*	Ridge/ smooth gourd	Fruit	15–20 Mg ha^{-1}
Lycopersicon esculentum	Tomato	Fruit	20–30 Mg ha^{-1}
Manihot esculenta	Cassava	Tuber	15–20 Mg ha^{-1}
Moringa oleifera	Moringa, drum's strick	Fruit	10–15 kg $tree^{-1}$
Momordica charantia	Bitter gourd	Fruit	25–30 Mg ha^{-1}
Musa paradisiaca	Banana	Fruit	1500 bunches (each of 18–22 kg)
Raphanus sativus	Radish	Root	25–30 Mg ha^{-1}
Solanum melongena	Brinjal	Fruit	20–35 Mg ha^{-1}
Spinacia oleracea	Spinach	Leaves	15–20 Mg ha^{-1}
Trichosanthes cucumerina	Snake gourd	Fruit	25–30 Mg ha^{-1}
Pulses			
Cajanus cajan	Pigeon pea	Fruit	500–600 kg ha^{-1}
Cyamopsis tetragonoloba	Guar, cluster bean	Fruit	600 kg ha^{-1}
Macrotyloma uniflorum	Horse gram	Fruit	500–700 kg ha^{-1}
Vigna radiata	Green gram	Seed	1–2 Mg ha^{-1}
V. mungo	Black gram	Seed	2–2.5 Mg ha^{-1}
V. unguiculata	Cowpea	Fruit	6–7 Mg ha^{-1}
Fruits			
Achras zapota syn Manilkara zapota	Sapota	Fruit	30–35 kg $tree^{-1}$ $year^{-1}$
Aegle marmelos	Bael	Fruit	300–350 fruits $tree^{-1}$ $year^{-1}$

(continued)

Table 13.5 (continued)

	Vernacular name	Economic produce	Average yield
Ananas camosus	Pineapple	Fruit	2–3 kg per plant
Annona squamosa, *A. ramosa*	Custard apple	Fruit	30–40 kg tree^{-1} year^{-1}
Artocarpus spp.	Jack fruit	Fruit	200–250 fruits tree^{-1} year^{-1}
Averrhoa carambola	Kamrakh	Fruit	75–125 kg tree^{-1}
Carica papaya	Papaya	Fruit	30–35 kg tree^{-1}
Citrullus lanatus	Watermelon	Fruit	25–35 Mg ha^{-1}
Citrus spp.	Citrus	Fruit	500–700 fruits tree^{-1} year^{-1}
Emblica officinalis	Gooseberry	Fruit	15–20 kg tree^{-1}
Mangifera indica	Mango	Fruit	150–200 kg tree^{-1} year^{-1}.
Musa paradisiaca	Banana	Fruit, stem	25–30 kg tree^{-1}
Psidium guajava	Guava	Fruit	30–50 kg tree^{-1}
Syzygium cuminii	Jamun	Fruit	60–80 kg tree^{-1}
Tamarindus indica	Tamarind	Fruit	200–250 kg tree^{-1} year^{-1}
Nuts/oil and fats			
Anacardium occidentale	Cashew tree	Nuts	5–8 kg plant^{-1}
Arachis hypogaea	Groundnut	Kernels	1.5–2.0 Mg ha^{-1}
Areca catechu	Areca nut	Nuts	10–12 kg palm^{-1}
Brassica spp.	Mustard	Seed oil	200–300 kg ha^{-1}
Cocos nucifera	Coconut nuts	Nuts	100–150 nuts palm^{-1}
Helianthus annuus	Sunflower	Flower/seed	400–500 kg ha^{-1}
Sesamum indicum	Sesame	Seed oil	800–900 kg ha^{-1}
Spices and condiments			
Cinnamomum zeylanica	Cinnamon	Bark	1.5–2 kg quills tree^{-1}
Curcuma longa	Turmetic	Rhizome	3–5 Mg ha^{-1} year^{-1}
Myristica fragrans	Nutmeg	Nuts	750–1200 nuts tree^{-1} year^{-1}
Piper nigrum	Pepper	Fruit	2–2.5 kg vine^{-1}
Syzygium aromaticum	Clove	Dry flower buds	2–3 kg buds plant^{-1} year^{-1}
Zingiber officinale	Ginger	Rhizome	10–12 Mg ha^{-1}fresh ginger
Others			
Saccharum officinarum	Sugarcane	Culm(juice)	20–25 Mg ha^{-1}
Zea mays	Maize	Grains	130–150 kg ha^{-1}

Source: Dagar (1995) also reported by Dagar et al. (2014)

(2004) also reported the yield of some vegetables and fruits in homegardens of Lakshadweep Islands. He observed varieties of chillies (*Capsicum* sp.) to produce 6.7–24.0 Mg ha^{-1}, brinjal (*Solanum melongena*) 20.3–33.7 Mg ha^{-1}, snake gourd (*Trichosanthes anguina*) 22.5 Mg ha^{-1}, cucumber (*Cucumis sativus*) 30.3 Mg ha^{-1} and tomato (*Lycopersicon esculentum*) 2.1 Mg ha^{-1}. Among fruits, varieties of banana are reported to yield 12.5–13.5 kg per plant, papaya 15.7 kg per plant, moringa (*Moringa oleifera*) 15 kg pods per plant and watermelon 2.4 Mg ha^{-1}.

Among tuber crops, 5 kg per plant was harvested from tapioca (*Manihot esculenta*) and 2 kg per plant from elephant foot yam (*Dioscorea* sp.), while sweet potato (*Solanum tuberosum*) could produce 1.6 Mg ha^{-1} tubers.

Diversity in different categories of trees differs among the homegardens across the islands. Palm trees registered the lowest diversity but the highest concentration of dominance in the homegardens of all the islands. Among the Andamans, fruit trees record the highest diversity in Middle Andaman and the lowest in Little Andaman. Similarly, spice trees register the highest diversity in Little Andaman and the lowest in North Andaman. All species diversity is the highest in the homegardens of Nicobar and the lowest in that found in the Andamans. In the homegardens, areca nut contributes maximum (54–76%) followed by coconut to the density in the homegardens as it provides economic security to households, whereas coconut serves the subsistence. Banana particularly var. *champa*, locally known as "*Cheena kela*", is most common, contributing about 85% to the total banana population. Pineapple is another fruit crop found relatively more common in the homegardens with quite high density, but the frequency was found to be low indicating its uneven distribution across the homegardens. Only few farmers (6%) are found to grow the fruit species for commercial purposes but maximum (94%) for household consumption. The perennial ligneous species like tamarind (*Tamarindus indica*) and *Ceiba pentandra* are found generally in each homegarden. The former serves as food, whereas the latter provides flosses which are used for making beds and pillows. Tree spices like clove, nutmeg and cinnamon are found in the homegarden, but the relative frequency of cinnamon is the lowest perhaps due to higher labour input, in harvesting, debarking and drying and comparatively low return.

13.4.2.2 Spatial and Temporal Arrangements of Plant Species in the Orchards

Temporal organization of crops is an important feature of homestead agroforestry. Temporal organization ensures round-the-year production in the system because of the difference in the biological cycle in the crops. Plantations such as coconut and areca nut bear flowers and nuts round the year. Harvesting in areca nut generally occurs from September to December, but maximum yields are found from October to November. Harvesting in coconut occurs from January to February for copra, but tender coconuts are harvested round the year. Areca nut-based system is very common in Andamans and tuber crops commonly cultivated partial shade-tolerant crops, and its trunk is commonly used as support for black pepper (Fig. 13.7).

MSCS and HG together account for 63% and 100% of farmlands of ANI and LDI. Analysis of HG of ANI has revealed a five-storey distribution of vegetation (Pandey et al. 2007), and the vegetation of LDI as per their height is fitted in different strata of AF systems. The general structure of MSCS (ANI) and HG of both islands are given in Table 13.6. In LDI, coconut is the exclusive crop cultivated, and owing to moisture limitations in sandy soils, understorey vegetation is less and more often limited to surroundings of the home only.

The crops of HGs vary a lot ranging from annual vegetables and pulses to grasses for animals. Vegetable crops are increasingly becoming the best bets for ground

Fig. 13.7 Areca nut plantations having tuber crop elephant foot yam (*Ammorphophallus campanulatus*) of Araceae at its base and trunk is utilized as support of black pepper (Photo credit: Dr. Ajit A. Waman)

vegetation for catering to the vibrant islands market (ANI) and household consumption (LDI) in small patches. Studies have indicated cucumber (*Cucumis sativus*) as the most profitable crop of coconut-based HGs (Nair et al. 2000) of Andamans. A tuber crop (Nicobar *aloo*, *Tacca leontopetaloides*) also known as Fiji arrowroot is the preferred vegetable crop in HGs of Nicobar and LDI. The wide accessions and relatives of this were collected in the islands by Dwivedi et al. (2013) for further research to improve their production in islands. New tuber crops and their improved varieties for higher income were demonstrated to Nicobarese farmers in lieu of Nicobar *aloo* by Damodaran et al. (2016), and kitchen garden concept was popularized by ICAR-CIARI, Port Blair, under Schedule Tribes Component (STC) scheme that has contributed to the diversification of food and income of Nicobar Islands.

In coastal and island regions, various varieties of banana—both vegetable and fruit varieties including exotics—are cultivated in almost all homegardens in isolated beds and along with other plantation crops (Fig. 13.8). There is good scope for the production of other tropical fruits like mangosteen (*Garcinia indica, G. cowa*), mango (*Mangifera indica)*, guava (*Psidium guajva*), sapota (*Achras zapota syn Manilkara zapota*), custard apple (*Annona squamosa*), pineapple (*Ananas comosus*), durian (*Durio zibethinus*), dragon fruit (*Hylocereus undatus*), rambutan (*Nephelium lappaceum*), jack fruit (*Artocarpus* spp.), grapefruit (*Citrus paradisi*) and longan

Table 13.6 Special and temporal arrangement of species in MSCS (ANI) and HGs of ANI and LDI

Storey (height, m)	MSCS (ANI)	HG		Remarks
		ANI	LDI	
Top storey (15–20 m)	Coconut, areca nut, cashew nut and rubber, red oil palm	Coconut, forest trees (if retained)	Coconut, *Terminalia catappa*	Understorey species may vary
Fourth storey (10–15 m)	Multipurpose trees (MPTs)	Areca nut, jack fruit; rubber	Areca nut, breadfruit (*Artocarpus altilis*) and jack fruit	In LDI, "Chakka" (*Artocarpus incisa*) tree is popular
Third storey (5–10 m)	MPTs, tree spices (clove, cardamom, nutmeg)	Tamarind, mango, cashew nut, guava, *Ceiba pentandra*	Tamarind, gooseberry, *Thespesia populnea*, *Ceiba pentandra*	For fuel and wood coastal plants used, for fence *Vitex negundo*, *Ficus* sp., *Gliricidia sepium*
Second storey (2–5 m)	Tree spices, black pepper as a climber	Tree spices, papaya, banana, *Morinda citrifolia*	*Moringa oleifera* and banana (fruit), *vazha* (plantain), betel leaf, *Morinda citrifolia*	Black pepper coconut/ areca nut in ANI
Ground storey (<2 m)	Pineapple, root crops, grasses (native and cultivated)	Turmeric, ginger, cassava, elephant foot yam, grasses and pineapple in ANI. In Nicobar, *Tacca leontopetaloides* is common, vegetable	*Chambu* (*Colocasia antiquorum*), yam, sweet potato, cocoyam (*Xanthosoma sagittifolium*), cowpea, vegetables	Vegetables on the terrace of homes in LDI

(*Euphoria longan*) which have high export potential. Malabar tamarind (*Garcinia gummi-gutta*), introduced in islands as a potential fruit tree sometimes back only, showed successful performance and found profitable bearing profuse fruits (Fig. 13.9).

In Andamans, dragon fruit (*Hylocereus undatus*) and carambola (*Averrhoa carambola*) have been tested and found successful and suitable (Figs. 13.10 and 13.11a, b) for these islands and may be cultivated on a large scale. Besides, poultry, pig and cattle can be integrated with the crop components for efficient resource recycling and provide stability to farm income.

Several cultivars of grasses such as *Andropogon gayanus*, *Brachiaria mutica*, *B. ruziziensis*, *Panicum maximum*, *Pennisetum purpureum*, *Setaria anceps* and *Tripsacum laxum* were successfully evaluated and found suitable along slopes and

Fig. 13.8 Banana and areca nut plantations along slopes, planted after forming the beds

Fig. 13.9 Malabar tamarind (*Garcinia gummi-gutta*), a profitable introduction in the islands, showing prolific fruit bearing in the underutilized fruits germplasm block, Garacharma Farm (Photo credit: Dr. Pooja Bohra)

Fig. 13.10 Performance of dragon fruit (*Hylocereus undatus*) in Andamans, trained in concrete pots (Photo credit: Dr. K. Abirami)

ground storey crops (Sharma et al. 1991; Dagar 1995; Dagar et al. 2014). Among legumes, *Stylosanthes guianensis* suits to acidic, saline-alkaline and waterlogged soils of ANI (Ramesh et al. 1999). Further, through leaf meal production from *Stylosanthes*, poultry (Ramesh and Gangaiah 2004) and pig (Yadav et al. 1990) production could be strengthened. Many trees of HGs like *Trema tomentosa*, *Macaranga roxburghii*, *Morinda citrifolia*, species of *Ficus*, *Gliricidia*, *Artocarpus* and many mangroves are being tapped for fodder in islands. The MPTs' use for livestock support in ANI has been documented by many (Sharma et al. 1990; Dagar et al. 2014; Jaisankar et al. 2015). Aromatics do have a place in HGs as ground vegetation in islands and other coastal areas. Lemon grass (*Cymbopogon flexuosus*) could be cultivated successfully along sloping lands as well as ground storey crop. Many medicinal plants such as *Colubrina asiatica*, *Morinda citrifolia*, *Curcuma domestica*, *Dioscorea* spp. and *Zingiber officinale* show their promise for these areas.

In MSCS/HGs of ANI, scope lies for fresh water aquaculture in ponds based on the collected and stored rainfall spread over 8–9 months in a year. A successful system based on fish farming (Indian major carps—Catla + Rohu + Mrigal: 5000 fingerlings per ha in 4:3:3 ratio), integrated with MSCS for sloping lands of ANI, was developed successfully by Chaturvedi et al. (2015). Banana, spices and vegetable (planted on bunds/dykes) litter form the part of fish feed directly. Bottom feeders (mrigal and common carp) utilize the detritus of organic particles. A fish harvest of

a

b

Fig. 13.11 (**a**) High-density orchard of carambola (*Averrhoa carambola*) grown with weed mat at Garacharma farm having (**b**) prolific bearing (Photo credit: Dr. Pooja Bohra)

2 Mg ha^{-1} when sold at a premium price (INR 250–500 kg^{-1}), considered reasonably good income, was availed.

Weed management through mulching (organic and plastic) was evolved to conserve precious water in HGs, and the same is suitable for organic farming also. Pressurized irrigation systems (drip) for the successful cultivation of vegetables (even for banana, papaya) on conserved water in ponds have been advocated. Nutrient recycling in coconut-based HGs indicating 90% and 65% of the negative balance for P and K (Pandey et al. 2011) necessitates its augmentation through the use of rock phosphate, K fertilizers and microbes. Vermicompost technology adoption in HGs will augment nutrient demands better and quicker. Tree habitation of rats is the most concerned biotic pressure of LDI and needs to be addressed effectively. Biotic control through the barn owl (*Tyto alba*) has been found effective. Farming system approach adoption and their organic mode of production will put HG produce at different strata and could give rich economic dividends (Swarnam et al. 2017). HGs of LDI are organic already, while ANI is working on certification process.

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. Distribution of the houses has no specific pattern, but house construction is preferred on uplands to avoid stagnation of rainwater. Ground cover, generally, is not cultivated for annual crops, but occasionally, it is cultivated for pineapple. A few smallholders (2–3%) grow *Curcuma longa*, *Zingiber officinale*, *Manihot esculenta* and *Ammorphophallus campanulatus* in the homegardens in South Andaman and only 8–10% in North and Little Andaman mainly for household consumption. Flowers like firecracker (*Crossandra infundibuliformis*), tuberose (*Polyanthes tuberosa*), marigold (*Tagetes erecta*) and jasmine (*Jasminum grandiflorum*) are grown a little in front of the houses and I*xora parviflora* on the boundary of homegardens. Coconut forms the top storey, whereas banana forms the first storey in Nicobar. A wild tuber (*Tacca leontopetaloides*) and grasses constitute the ground flora in these homegardens.

In LDI, coconut is the main crop of economic importance. Due to rapid fragmentation of landholdings, farmers grow coconut trees in closer spacing, which has resulted in low yield. It has been estimated that on an average, 400–500 palms of all ages are found growing in 1 ha of land as against 170–200 normally recommended for optimum yield. It was found to yield about 135 nuts per palm per year in normal spacing and 40 in double the density of planting (Jacob 2004). As the organic content in soil of these islands is very low and the water and nutrient holding capacity of the soil is very poor, to increase the productivity, vermicomposting of coconut waste was found useful. Experiments conducted in Minicoy 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* 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 and feasible to increase the productivity of coconut gardens in islands (Jacob et al. 2002; Jacob 2004).

13.4.2.3 Carbon Sequestration in Homegardens

It has now been established that the soil C can be increased to new higher equilibria with sustainable management practices and adoption of appropriate farming systems such as agroforestry (Nair et al. 2010). The rate of average global C sequestration was estimated to be 33.8 and 33.2 g C m^2 year^{-1}, respectively, due to changing land use from agriculture to agroforestry or grassland (Post and Kwon 2000). The carbon sequestration in humid and subhumid 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. Tropical homegardens with high agro-biodiversity have been reported to have high potential for C sequestration. Kumar and Takeuchi (2009) and Kumar (2011) studied C stock of mixed-species homegardens (numbered 839) in Kerala state of Western Coast and found that aboveground C stock of trees (>20 cm girth) ranged from 16.3 to 35.2 Mg ha^{-1} with a mean of 24.3 Mg ha^{-1}. Saha et al. (2010) also reported similar results for soil organic carbon stocks in the homegardens of Thrissur, Kerala.

13.4.3 Multi-Enterprise Farming Systems/Aqua-Silviculture Systems

This agricultural system is the most promising, sustainable and economically viable. In coastal areas, aquaculture (shrimp and fish) in association with paddy cultivation or in denuded mangrove areas is an age-old practice. On the bunds of fish ponds, plants of coconut palm and banana and a few other fruit trees are grown quite frequently. Many farmers also grow vegetables on dykes of fish ponds. Despite the fact that most of the small families are dependent on this system of cultivation, very little research efforts have been made to improve this cultivation. During the last two decades, efforts have been made to develop integrated farming systems particularly in waterlogged areas involving fish/shrimp culture in fish pond, live-stock, food and forage crops, vegetables, fruit trees on dykes, poultry/duckry, piggery (if feasible, e.g. in Nicobars) and plantation crops as components. This is the best example of an advanced agroforestry system which gives stability in production and income throughout the year in odd situations of climate.

Recently, the concept of this farming system has been interpreted and adopted through agricultural universities in coastal states. Components like horticulture, sericulture, forestry, fish culture and poultry 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 yield from the traditional paddy cultivation in coastal saline lands, brackish water fish (*Penaeus monodon*) and fresh water fish like *Tilapia mossambica*, *Mugil passia* and *Mugil tade* have been found most remunerative in situations like West Bengal and Orissa. Integrated farming system approach combining field, horticulture and plantation crops; livestock (dairy), biogas and goatery; and silviculture proved to be a viable preposition for marginal and small farmers under dryland/rainfed situation (Mahapatra and Panda 1994).

An integrated farming system was evaluated on farmers' field of Cuttack district of Orissa (Mohanty et al. 2004). Out of 2.5 ha waterlogged area, 1.64 ha was converted into a fish pond, while vegetables, flower and fruits were grown on raised embankments. During stocking, a density of 7500 fingerlings per ha was maintained in a fish pond with species composition of 30:40:15:15 (*Catla catla*:*Labeo rohita*:*Cirrhinus mrigala*:*Cyprinus carpio*). In addition to this, prawn post-larvae of *Macrobrachium rosenbergii* were also stocked in the main pond for polyculture with Indian major carps (at 15000 per ha). Poultry sheds were also constructed for rearing about 4000 birds in such a way that droppings could fall into the pond as organic manure and feed for fish. The average productivity of fish and prawn culture alone was 8.1 Mg ha^{-1} per annum, and gross and net return from fish and prawn in 2002 was INR 376,317 ha^{-1} and 201,868 ha^{-1}, respectively. This accounted for INR 14 m^3 of water productivity in the pond system alone. The gross and net returns from the whole system of 2.47 ha during the year were INR 651,110 (INR 2,63,607 ha^{-1}) and INR 362,515 (INR 1,46,767 ha^{-1}), respectively. Thus, the system was found to be the most profitable and sustainable.

Most of the coastal aquatic animals including fish utilize the mangrove water as nursery and breeding grounds. A variety of these animals gets associated with mangroves and makes complex but interesting food web. Mangroves through their leaf litter contribute substantially the nutrients to fisheries in the adjacent coastal waters. There are many forms of aquaculture, such as oyster, crab, fish and prawn culture enclosed in either pans or cages, which may be undertaken in mangrove swamps without destruction of the habitat. In many coastal areas, shrimp culture is practised by means of pond construction behind mangrove areas. The ponds are connected to coastal waters through channels, and during daily high tides, the water flows into the pond. The outflow of water and shrimps is controlled by sluice gates. Species of *Avicennia*, *Sonneratia*, *Rhizophora*, *Bruguiera*, *Ceriops* and *Cynometra* are considered good fodder trees and may be raised in paired rows (1–2 m apart) in mangrove swamps. On maturity, the alternate rows may be harvested for fuel and fodder. Some low-lying areas which are partially reclaimed are being used in Andamans for coconut cultivation. Andaman Tall and Katchal Tall varieties perform well yielding 30–65 nuts per palm per year. These may be planted on dykes of fish ponds along with other MPTs like *Morinda citrifolia*. On raised bunds, fodder grasses such as guinea (*Panicum maximum*), thin napier (*Pennisetum* sp.), Guatemala (*Tripsicum laxum*) and stylo (*Stylosanthes guianensis*) could perform well.

13.4.4 Silvopastoral Systems (Cut and Carry Systems/Fodder Farming)

Though silvopastoral system refers to land use system in which pasture (grazing land) and livestock production are integrated with woody perennials (mainly nitrogen-fixing leguminous trees) on the same land management unit and grazing is a major component, but here, the concept covers broadly "cut and carry" fodder production practices. In the cut-and-carry system, the field is protected from grazing and forages both herbaceous species and trees which are harvested in a planned way on regular intervals and are fed to livestock outside the field. In this system, the production is more, and there is no plant damage due to trampling. The trees in managed species have a great potential for efficient cycling of plant nutrients. Growing of nitrogen-fixing trees has additional advantage as these help in fixing the atmospheric nitrogen into the soil which in turn is utilized by the associated field crops. Mathew et al. (1992) in Kerala revealed that growth and yield of fodder species significantly influenced by tree components only after tree canopy formation. The fodder grass species such as *Pennisetum purpureum*, *Panicum maximum*, *Brachiaria ruziziensis* and *Euchlaena mexicana* grown in association with trees, namely, *Casuarina equisetifolia* and *Ailanthus malabarica*, recorded higher forage yield even after canopy formation as compared to without trees. However, forage yield in association with *Acacia auriculiformis* and *Leucaena leucocephala* was relatively lower. The forage grasses performed in order *P. purpureum* > *P. maximum* > *B. ruziziensis* > *E. mexicana* producing mean biomass 74.5, 59.0, 42.5 and 23.9 Mg ha^{-1}, respectively.

There are many opportunities of growing salt-tolerant fodder trees in situations like wetlands of West Bengal. Besides fodder trees, forage grasses such as *Coix lachryma-jobi, Brachiaria mutica* and *Echinochloa* spp. can successfully be cultivated giving three to five cuts in a season. Based on the average of 2 years data obtained by Biswas (1994), these grasses could produce 41.3, 31.1 and 24.4 Mg ha^{-1}, respectively, forage biomass from five cuts during *Kharif* season. When applied, 60, 80, 100 and 120 kg nitrogen *Coix lachryma-jobi* could produce 39.2, 43.5, 48.4 and 50.0 Mg ha^{-1}, respectively, forage biomass showing that 100 kg nitrogen per ha is sufficient to get optimum yield from this grass, which grows well in stagnant water.

In one experiment, Kumar et al. (1998), after 7 years of growth of trees, obtained aboveground biomass of 73.4, 7.8, 13.5 and 25.4 kg per tree and 183.5, 19.4, 33.7 and 63.5 Mg ha^{-1}, respectively, with an annual mean increment of 26.2, 2.8, 4.8 and 9.1 Mg ha^{-1} $year^{-1}$, respectively, from *Acacia auriculiformis*, *Ailanthus triphysa*, *Casuarina equisetifolia* and *Leucaena leucocephala*. The performance of understorey herbage production of four forage grasses under *Acacia auriculiformis*, *Ailanthus triphysa*, *Casuarina equisetifolia* and *Leucaena leucocephala* was observed by Kumar et al. (2001a, b) and found that herbage production increased until 3 years in all tree + grass combinations but declined subsequently, as the tree crown expanded after 3 years. Overall, *Casuarina* among above-mentioned trees and hybrid napier (*Pennisetum purpureum*) and guinea (*Panicum maximum*) among forage crops (other forage crops were congo signal—*B. ruziziensis* and teosinte—*Zea mexicana*) performed better than others.

In Andamans, there is about 8300 ha of fallow lands and permanent pastures which can be upgraded or used for fodder cultivation and about 12,000 ha of barren and culturable wastes which can be managed as high-quality pasture lands. The soil cover under sizeable area of coconut and rubber plantations could also be developed for perennial fodder cultivation in all the coastal areas. The productivity of local grasslands is very low. In one study, Sharma et al. (1991) and Dagar (1995, 2000) reported dry forage biomass ranging from 20.5 Mg ha^{-1} in Kazungula cultivar of *Setaria anceps* to 34.0 Mg ha^{-1} in Guinea (*Panicum maximum*) under multiple cuts in a year (6–9 cuts) in the cut-and-carry system on sloping lands in Andamans. Other grasses included *Andropogon gayanus* (28.7 Mg ha^{-1}), *Brachiaria mutica* (28.1 Mg ha^{-1}), *B. ruziziensis* (33.2 Mg ha^{-1}), *Paspalum plicatulum* (33.3 Mg ha^{-1}), *Pennisetum purpureum* (30.5 Mg ha^{-1}) and *Tripsicum laxum* (20.6 Mg ha^{-1}). The legume species of this system included calopo (*Calopogonium mucunoides* 10.9 Mg ha^{-1}), sirato (*Macroptilium atropurpureous* 4.5 Mg ha^{-1}), cordofan pea (*Clitoria ternatea* 8.7 Mg ha^{-1}) stylo (*Stylosanthes guianensis* with 23.4 Mg ha^{-1} and *S. scabra* with 10,5 Mg ha^{-1}); each obtained from two cuts. *Leucaena leucocephala* produced 22.3 Mg ha^{-1} leaf foliage from six loppings. These forages also perform well in wider spaces of fodder trees like *Trema tomentosa*, *Morinda citrifolia* and *Leucaena leucocephala*. *Morinda citrifolia* has been identified, adopted and domesticated as very useful MPTs by local people, and they prepare several products from its fruit. The goats enjoy the leaves of *Trema tomentosa*; hence, locally, the tree is known as *bakri-patta* (goat-leaves). Moreover, the grasses such as thin-napier and guinea and legume stylo have high potential to propagate naturally through seed once introduced. These may also be raised after the protection of grazing lands and under old coconut or areca nut plantations. In wider spaces of these plantations, nitrogen-fixing trees like *Gliricidia sepium* can be grown, which may also be used as support for black pepper and improved fodder grasses such as napier or guinea or *Panicum* grass which can be cultivated successfully. Leguminous species mentioned above are good cover crops and may also be cultivated as interspace crops in red oil palm and rubber plantations. These not only provide nutritious fodder but also increase soil fertility and protect it from erosion.

Multipurpose trees such as *Aegle marmelos*, *Artocarpus* spp., *Bauhinia variegata*, *Erythrina variegata*, *Ficus* spp., *Grewia glabra, Hibiscus tiliaceus*, *Moringa oleifera*, *Pithecelobium dulce*, *Pongamia pinnata*, *Samanaea saman*, *Sesbania grandiflora*, *Pongamia pinnata* and *Trema tomentosa* are growing successfully in these islands and may be raised as fodder banks.

13.4.5 Hedgerow (Alley) Cropping

This is one of the modern well-researched systems of growing small trees or shrubs in wide rows. This is mainly suitable and usually adopted for sloping lands where forage shrubs are planted across the slope and forage grasses and legumes or crops in

Table 13.7 Performance of forage crops and *Gliricidia sepium* in alley cropping system (Mg ha^{-1})

Fodder crop	Dry forage yield			Dry weight of *Gliricidia* lopping		
	Without *Gliricidia*	With *Gliricidia*	Reduction in yield (%)	Stick	Foliage	Total
Pennisetum purpureum (hybrid napier)	14.7	7.4	49.7	3.2	5.1	8.3
Setaria anceps (Kazungula)	9.8	7.0	28.6	8.7	15.0	23.7
Panicum maximum (Guinea)	10.8	9.4	13.5	5.4	12.2	17.6
Stylosanthes guianensis (Stylo)	5.4	3.5	34.4	5.6	10.0	15.6
LSD ($p \leq 0.05$)	3.6	3.3	–	–	–	–

Source: Modified from Dagar (1995)

the interspaces. Two parallel rows usually 1 m 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. *Gliricidia sepium*, *Leucaena leucocephala*, *Cassia siamea*, *Morus alba*, perennial *Cajanus cajan* and *Pithecelobium dulce* are trained as hedgerow crops. The hedges are frequently cut at about 1 m height from the ground, and the sticks are usually used as fuelwood and foliage as fodder or mulch. *Gliricidia* is more popular in tropical regions across the globe including Indian coasts.

Dagar and Kumar (1992) conducted one experiment in high-rainfall area of Andamans, where *Gliricidia sepium* was established from cuttings of mature plants, planting across the slope in alleys on a gravely sloping land. Four herbaceous fodder species, hybrid napier (*Pennisetum purpureum),* kazungula (*Setaria anceps*), guinea (*Panicum maximum*) and stylo (*Stylosanthes guianensis*) were cultivated in interspaces. After 1 year of establishment, *Gliricidia* yielded 6.1 Mg ha^{-1} of dry lopped biomass in two cuts. During the second year, the yield of lopped *Gliricidia* and intercrops increased abruptly owing to gap filling and greater branching (Dagar 1995). Forage crops produced 3.5–9.4 Mg ha^{-1} dry forage biomass, but due to root competition, the biomass was reduced from 13.5% in guinea grass to 49.7% in hybrid napier grass (Table 13.7).

13.4.6 Taungya

Taungya is a traditional system of establishing commercial forest plantations such as *Tectona grandis*, *Eucalyptus* spp. and *Ailanthus triphysa* in which agricultural crops are cultivated on a temporary basis between regularly arranged rows of trees. The greatest disadvantage of taungya system established on sloping lands, however, has been soil erosion caused by bed preparation for the cultivation of arable crops. The system is widely practiced in the Western Ghats. While cultivating 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% that shows the disadvantage of this system without taking measures of soil conservation on a sloping land, particularly in high-rainfall areas. Many of the nitrogen-fixing species can convert substantial quantities of atmospheric nitrogen into a combined form (Danso et al. 1992) and can successfully be utilized to improve taungya plantation stands. The growth of teak was reported to increase in Java when planted in the association of *Leucaena* (Van Noordwijk et al. 1996) and growth of *Eucalyptus saligna* was significantly more when it was interplanted with nitrogen-fixing *Albizia falcataria* (Binkley et al. 1992).

Leucaena has been reported to fix 100–150 kg of nitrogen ha^{-1} year^{-1} (Dommergues 1987). A significant portion of this nitrogen is released into the rhizosphere through leaf litter, fine roots and nodule turnover. Associated crops may utilize the nitrogen so released (Mathew et al. 1992). Effects of intercropping of teak with *Leucaena* were studied by Kumar et al. (1998) in their experiments conducted in Kerala and observed the significant increase in tree growth and the system also improved soil characteristics. Forty-four months after planting teak with *Leucaena* (two rows of *Leucaena* for every row of teak), the height of teak was 45% more, and diameter at breast height (DBH) was 71% higher than those in pure stands. Total N content of the soil increased with the increasing relative proportion of *Leucaena*; available P levels were highest in the 1:1 teak-*Leucaena* mixture, while available K was highest in the 1:2 mixture. Despite the favourable effects of intercropping *Leucaena* on teak growth, increasing the relative proportion of *Leucaena* substantially (>50%) may be counter-productive, as it would substantially reduce teak density. A 50% mixture (alternate rows of teak and *Leucaena*), therefore, is considered optimal. Therefore, if *Leucaena* is planted in alternate rows with teak, intercropping with agronomic crops might be profitable, and a substantial quantity of firewood could be produced in these improved taungya agroforestry systems.

13.4.7 Woodlots

These days agriculture has become labour-oriented, and private industrial forestry has become a recent phenomenon. The farmers with medium to large holdings are found to integrate trees with field crops and/or animal production. At many places, they raise MPTs as woodlots to have enhanced income and avoid labour investment. Plantations of *Eucalyptus*, *Casuarina*, *Bambusa* and *Acacia auriculiformis* are quite frequent all along coastal regions. Commercial plantations (woodlots) such as of cashew nut (*Anacardium occidentale*) are quite common near Goa on West Coast and Puri on East Coast. Despite raising woodlots of MPTs, very limited efforts have been made for systematic studies of these woodlots regarding their biomass production and nutrient use efficiency. Kumar et al. (1998) estimated tree biomass of nine MPTs at 8 years and 10 months of their growth. Biomass accumulation showed wide variations, and the aboveground biomass was highest (326.4 Mg ha^{-1}) in *Acacia* *auriculiformis* followed by *Paraserianthes falcataria* (183.5 Mg ha^{-1}), and minimum (22.8 Mg ha^{-1}) was from *Leucaena leucocephala*. Degraded mangrove areas are the ideal situation of raising fast-growing species of mangroves facing sea and associate mangroves such as species of *Casuarina*, *Pongamia*, *Terminalia*, *Callophyllum* and many others bordering them.

13.4.8 Live Fences and Hedges

Many MPTs are found grown on field boundaries by the farmers in coastal and island regions. *Ailanthus excelsa*, *Bambusa* spp., *Borassus flabellifer*, *Casuarina equisetifolia*, *Cocos nucifera*, *Carissa carandas*, *Cordia rothii*, *Dalbergia sissoo*, *Ficus* spp., *Leucaena leucocephala*, *Moringa oleifera*, *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 the Gujarat region, *Prosopis juliflora* is commonly trained as a protected hedge on farm boundaries along with species of *Agave*, *Capparis* and cactus such as *Cactus indicus*, *Cereus peruvianus*, *C. triangularis*, *C. hexagonus*, *Opuntia dillenii*, *O. monocantha* and *O. tuna*. All along the Orissa coast, *Casuarina*, *Pandanus* and *Acacia auriculiformis* are very common in open as well as boundary plantations. Many plant species are grown as live fence and hedges around farms and homegardens which include *Bambusa* spp., *Vitex trifoliata*, *V. negundo*, *Jatroph*a *gossipifolia*, *Ficus rumphii*, *Agave sisalana*, *Ehretia microphylla*, *Clerodendrum inerme*, *Duranta repens*, *Erythrina variegata*, *Lawsonia inermis*, *Pithecellobium dulce* and *Gliricidia sepium.* There is a need of systematic research in this field. In one trial with *Leucaena leucocephala*, about 23.3 Mg ha^{-1} dry biomass was obtained in six cuts round the year when planted densely (50 cm × 50 cm) as hedge crop (Sharma et al. 1990). *Carissa carandas*, *Gliricidia sepium* and *Pithecellobium dulce* also perform well in the islands. *Ceiba pentandra*, *Casuarina equisetifolia*, *Gliricidia sepium* and *Vitex negundo* are quite common in paddy fields. Many plants coppice well and are mentioned under multipurpose woody perennials, but more research is needed to find out more suitable species for live fences and hedges.

Bamboos occur extensively in the managed ecosystems both as plantations and in agroforestry as scattered clumps as well as hedgerows on farm boundaries. Now, the bamboo is considered to be an important livelihood strategy of rural people and is being elevated from a raw material known as the “poor man’s timber” to the status of “timber of the twenty-first century”. Among the ~130 wild and cultivated bamboo species reportedly occurring in India (Sharma 1987), thorny bamboo (*Bambusa bambos*) is considered the most important in the life of rural people along the West Coast of India. Kumar et al. (2005) studied aboveground biomass production and nutrient uptake when bamboo was grown as hedgerow and the biomass averaged 2417 kg per clump with an average accumulation of 242 Mg ha^{-1}. Highest biomass accumulation (82%) was observed in live culms followed by thorns + foliage (13%)

and dead culms (5%). Nutrient (NPK) export at harvest was also in the same order. Average N, P and K removal was 9.22, 1.22 and 14.4 kg per clump, respectively. Litter accumulation on the forest floor averaged 9.1 Mg ha^{-1} accounting for 482, 367 and 430 kg ha^{-1} of N, P and K, respectively.

13.4.9 Shelterbelts and Shore Protection

Coastal soils are sandy in texture with acidic pH at times too low behind mangroves due to oxidation of pyrite present in these soils, high electrical conductivity, sodium absorption ratio (SAR), poor in nutrients, water holding capacity and having shallow water tables. The coastline is challenged by oceanic waves and cyclonic winds from all sides in contrast to the one side impact of coastal states of India and needs permanent protection from erosion. In this direction, native vegetation and manmade plantations (shelter belts) are used together. In coastal areas, high winds also carry salt with them and damage crops. Many trees and shrubs such as *Casuarina equisetifolia*, *Acacia auriculiformis* and *Gliricidia sepium* may play a very important role in reducing the speed of these winds and may protect the crops from injury. These not only protect the crops but also help in soil amelioration. Most of the coastal areas are prone to damage caused by cyclones and even tsunamis. Mangroves have very dense root systems and protect the shore from the damage caused by these natural disasters. We must protect and conserve all the present stands, and all afforestation programs must be at place to restore the mangrove degraded areas by planting suitable species. Besides mangroves, littoral species such as *Pandanus* spp., *Thespesia populnea*, *Scaevola taccada*, *Tournefortia ovata*, *Hibiscus tiliaceus* and *Salvadora persica* may also play an 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 wildlife.

Littoral forests of ANI have tall evergreen *Manilkara littoralis* as the most characteristic species that with few deciduous trees (*Pongamia pinnata*, *Morinda citrifolia*, *Erythrina variegata*, *Calophyllum inophyllum*, *Terminalia catappa*, *Barringtonia asiatica*, etc.) form the dominant canopy. Numerous shrubs (*Thespesia populnia*, *Hibiscus tiliaceus*, *Pandanus* spp.) with grasses and surface creepers and sand binders (*Ipomoea pes-caprae*, *Crinum asiaticum*, *Vigna retusa*, *V. marina*, *Scaevola frutescens*, *Mucuna gigantea*, *Colubrina asiatica*, *Caesalpinia bonducella*, *Thalassia hemprichin* and *Cymodocea isoetifolia*) are seen. Dagar and Minhas (2016) and Ragavan et al. (2019) have given an excellent account on the understanding of mangroves and their associates, particularly in India. Their zonation pattern will make us understand where we must plant a particular species for a particular purpose. In LDI, mangrove forests are meagre, while littoral forests are common. This native vegetation is in both islands which is strengthened with *Casuarina* block plantation all along the coasts that together are protecting the shores, besides providing valuable forest products and sheltering wildlife. Mangroves such as *Avicennia marina* are tolerant to biotic stress and can easily be planted through seedlings in shallow waters. *Casuarina* and *Anacardium occidentalis* form excellent belt along beaches which can be grown as commercial plantation. *Nypa fruticans*, a mangrove palm, can successfully be grown as a commercial crop (yields alcohol) on protected muddy shores.

13.4.10 Aqua-Forestry

Aquaculture keeping mangroves intact is the most feasible and sustainable option for the promotion of aquaculture in inundated areas. After creating embankments, coconut and multipurpose trees like Noni (*Morinda citrifolia*) can be grown on raised bunds and in channels as well as mangrove creeks; fish or shrimp culture is quite feasible. In a preliminary study, mullet, prawn tilapia and fish culture could be made feasible and poof table connecting these culture ponds with brackish water behind mangroves particularly in association with *Avicennia* communities. The yield of shrimp fry (*Penacus* and *Metapenaeus*) was up to 690 kg ha^{-1} year^{-1}, and during the rainy season, 3 Mg ha^{-1} of rice could also be produced. *Nypa fruticans,* a mangrove palm (frequent in Sunderbans and Andaman-Nicobar Islands), is cultivated in the Philippines and Bangladesh as a commercial crop. The alcohol production was reported about 15,000 litres ha^{-1} year^{-1} (Vannucci 1989). This must be tried in islands and Sunderban areas. Fish/prawn culture keeping mangrove intact is a very viable and useful system particularly in areas where fresh water streams merge with seawater. Bee humps are natural in Sunderbans; hence, beekeeping and duckry/poultry can be blended with fish culture associated with mangroves particularly along creeks. The agri-silvi-aquaculture system of *tumpang sar*-approach of Indonesia is the ideal solution for producing shrimps with the least disturbance to the mangrove ecosystem.

In coastal and island areas, fish and prawn culture in constructed ponds (by converting paddy fields or destructing mangroves) is age-old practice on a large scale which has become the prime cause of mangrove destruction (Thomas et al. 2017). In ANI, mangroves are spread on 617 km^2 (FSI 2017), and their conversion to aqua-farms is minimum; however, their exploitation through mariculture (shrimp, crab, mussel) is possible (Dagar et al. 2014). In undulating terrains and flat topographies (paddy fields), check dams/farm ponds have been dug (there were 2095 ponds in ANI during 2017–2018), and there are many small channels with year-round water flow which are suitable for fish culture. There is a 185 ha pisciculture area in ANI (2017–2018). Trees (especially coconut), shrubs such as *Gliricidia*, *Leucaena*, *Moringa*, papaya, vegetables and grasses are planted on aquaculture ponds on earthen embankments, and leaves of this vegetation serve as “forage” for fish. Legumes, shrubs and their twigs and leaves serve as green leaf manure, and small branches and twigs of shrubs and trees serve as cooking fuel and fruits as human food. It is thus considered as a multi-enterprise and fish are ultimately used

Fig. 13.12 Aquaculture keeping mangroves intact (coconut in the background) (Photo JC Dagar)

for human consumption. Trees/shrubs besides providing forage to fish also aid in bund stabilization of ponds.

Degraded mangrove areas may be brought under productive use for mariculture keeping the mangrove species such as species of *Avicennia*, *Bruguera*, *Ceriops*, *Sonneratia*, *Rhizophora*, *Exoecaria* and *Cynometra* (Dagar et al. 1991, 2014) intact (Fig. 13.12). Species such as *Pandanus*, *Nypa* and Noni (*Morinda citrifolia*) which are extensively growing in mangrove areas of ANI could also be utilized for rehabilitation of degraded areas, and these have commercial uses like perfume and flavouring ingredient (pandanus), liquid and gaseous fuel, neera for jaggery making (*Nypa*) and feed and pharmaceuticals (noni). An Integrated Mangrove Fishery Farming System (IMFFS) was tested in mangrove wetlands by M. S. Swaminathan Research Foundation (MSSRF) with protective (mangroves) and productive (fisherman) functions. In seabass (*Lates calcarifer*), candidate fish of IMFFS, production was enhanced by 12.5% with pellet feeding (Venkatachalam et al. 2018). The mangrove trees also provide fuel and fodder, while Noni fruits are used in pharmaceuticals. Cage culture system developed in ANI (Anuraj et al. 2018) may further be the case of aqua-forestry in mangroves of islands. Aqua-forestry, however, is not possible in sandy soils of LDI, and mangroves are existing on only 2 ha. In Nicobar, farmers of late are evincing keen interest in aqua-forestry.

In December 2004, due to tsunami, about 4000 ha of agricultural land was inundated in Andaman and Nicobar Islands causing significant alteration to the agricultural production. The soil became acid sulphate (pH varying between 3.5 and 6.5, the bulk density of surface soil from 1 gm to 1.4 gm cm^{-3} and organic carbon from 1.5% to 1.8%). As a result, the farmers were forced to search for a viable alternative livelihood. The reclamation of saline acid sulphate soils for brackish water aquaculture can be achieved only through a model, which nullifies or reduces the above-mentioned problems. A procedure involves drying and filling of the soil to

Fig. 13.13 Left: Marine cage culture (Source: Annual Report 2016–17 of ICAR-CIARI, Port Blair). Right: Mud crab fattening (Photo credit: Mr. Prosenjith Samadder).

oxidize pyrite, filling the pond with water and holding till water pH drops to below 4 and then draining the pond with water, repeating the procedure until the pH stabilizes over and above 5. Several experiments on farmers' field were conducted (Dam Roy and Krishnan 2005; Dam Roy et al. 2005) at several sites with an idea to tackle these problems and to achieve a better productivity. There was notable improvement in soil and water pH during the culture period.

In such areas, ponds are made with a regulator to let in the high tide ocean water and let out the same at low tide while maintaining a minimum required depth of water in the pond for fish survival. Daily exchange of water between sea and pond results in the maintenance of required salinity for mariculture. Marine cage culture has also been found successful behind mangroves, and crab fattening (water crabs were introduced and fattened by feeding with trash fish or chicken meat or its wastes) was successfully demonstrated by KVK in Andamans (Fig. 13.13) and was followed by some farmers with high revenues (300%) in a short period of 3 weeks. Coconut, areca nut, fruit trees (mainly banana) and grasses are grown on bunds with crabs in ponds. Integration of duck was found to increase the productivity of aqua-forestry. Land-shaping interventions (shallow furrow and medium ridge, broad bed and furrow, farm ponds, paddy-cum-fish culture) for aqua-forestry gave higher income (Burman et al. 2015) than rice crop alone in ANI tsunami lands.

Artisanal fishing of islands demands wood regularly for canoe (dugout) making. A canoe is also known as *hodi/Ap/Ri* in Nicobar and is used for fishing and racing. These are made from *Calamus andamanicus*. In ANI and LDI, *Calophyllum inophyllum* (Mast wood/Punna) wood is also used in boat making. Its leaves contain compounds that are poisonous to fish and can be used as fish poison (Orwa et al. 2009). This can also be viewed as part of aqua-forestry though both are not linked directly and practiced separately. Dagar and Dagar (1991, 1999) have described in detail the art of canoe making and tree and other species used by the aborigines of Andaman-Nicobar Islands in their livelihood security including ethno-medicines.

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Shrimp or fish farming is one of the viable commercial alternatives to agriculture in these areas. The development of brackish water aquaculture especially shrimp farming has been one, and it has been found to have substantial economic gains. In series of experiments conducted in Andamans, it was found that there is the feasibility of culturing mud crab (*Scylla serrata*) in brackish water ponds filled during tide (at stocking density from 1000 to 5000 per ha). The highest production of 878 kg ha^{-1} during 8 months was obtained at a stocking density of 5000 ha^{-1}. The fattening of milkfish (*Chanos chanos*) was done for a period of 1 year and 4 months, and the net production at harvest was 1030 kg ha^{-1}. The mullet (*Liza tade*) seeds were stocked at stocking densities ranging from 6000 to 30,000 per ha, and the production rate varied from 111 to 342 (average 232) kg ha^{-1}. The production of seabass (*Lates calcarifer*) at 66% survival was found to be 3 Mg per ha. Two species of prawns, namely, the tiger (*Penaeus monodon*) and banana prawn (*Penaeus merguensis*), were cultured at a stocking density varying from 30 to 100,000 per ha, and with 60% survival, it was estimated to produce 1.3 Mg ha^{-1}in 120 days. Tilapia (*Oreochromis urolepis*) with 87% survival could produce 1036 kg per ha in 6 months. Thus, the vast inundated wetlands of South Andaman can be looked upon as a site promising innovative shrimp farming, which will be an alternate livelihood source for the farmers affected by the tsunami. On dykes of the ponds, plantations such as multipurpose Noni (*Morinda citrifolia*) or coconut and fruits like banana and guava can successfully be grown.

Carp culture in fresh water has been an important activity in coastal West Bengal and Bay Island, and about 90% fish farmers in North and South Andaman are frequently culturing a mixture of Rohu, Catla and Mrigla constructing ponds (Fig. 13.14). The indigenous cultivated species of carps include *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*, and the market value of these carps is very high (INR 200 per kg). Cat fish (Magur), also called "walking cat fish", is commonly found in fresh water mainly as swampy water ditches, ponds and paddy fields in rainy season. Another carp *Clarieas batrachus* commonly called as "Indian Magur" is commercially important fresh water species fetching high price (INR 300–400 per kg). *Channa striatus* (snaked head fish because of its flavor and boneless nature) and *Channa marulius* (Giant murrel) are also quite popular in the islands. The air-breathing fishes such as Singhi and Magur can successfully be cultivated in paddy fields of the Bay Islands during the rainy season (Dam Roy et al. 2005). Integrating fish culture with one or two live stocks at a time is quite often practiced. The concept of integration of fin and shellfish culture with agriculture (paddy), horticulture, piggery, duckery, poultry and livestock is a quite old traditional way of farming in the islands that has been refined over the years.

13.4.11 Apiculture with Trees

Honeybees are associated with forests (trees) since time immemorial in which flowers of forest provide subsistence (pollen) for honeybees and shelter for a swarm or beehive and bees in turn facilitate pollination of plants. This association

Fig. 13.14 Pond-based fish farming (Photo credit: Dr. K. Saravanan)

was exploited by purposeful planting of trees for supporting honeybees or introducing honeybees into existing tree vegetation. Crops (including plantations) and fruit orchards with other multipurpose trees (MPTs) could also support honeybees. The practice is common in all the coastal areas, but honey collection in Sunderbans is more popular and at times has been correlated with tiger attacks.

In ANI, mangroves support honey production particularly in tribal habitats. Honey collection for food is quite well-documented among aborigines of Andamans among Onges, Jarwa and Shompen tribes from historical periods from native bees *Apis dorsata* and *A. florae* (Dagar and Dagar 1991, 1999). The smearing of sap from *Orophaea katschalica* tree leaves on the body of honey collector to repel the *A. dorsata* bees depicts adaption mechanism. Introduction of *A. cerena indica* (in the 1970s) has further helped in apiculture in ANI. Studies in Little Andaman mangroves (three sites of Dungong creek and two sites of Jackson creek) have indicated that honey of two Dugong sites as unifloral (>45% pollen contributed by a single plant species called as predominant pollen type) and pollen is coming from *Sonneratia apetala* and *Barringtonia racemosa* (Shilpa Singh and Ratan Kar 2011). In other sites, pollen is multifloral and comes from 20 trees (including above two species) which include *Acacia auriculiformis*, *Albizia lebbeck*, *Barringtonia racemosa*, *Clerodendron inerme*, *Cocos nucifera*, *Excoecaria agallocha*, *Lagerstroemia parviflora*, *Lumnitzera racemosa*, *Nypa fruticans*, *Phoenix sylvestris*, *Pongamia pinnata*, *Rhizophora apiculata*, *R. mucronata*, *R. stylosa*, *Salmalia saman*, *Sonneratia alba*, *Syzygium cuminii*, *Terminalia catappa*, *Thespesia populnea* and *Xylocarpus* spp. These mangrove sites have potential to support medium- to large-scale beekeeping potential. In LDI, mangroves have little scope to support apiary, but from coconut plantations, honey production is quite possible. In Little Andaman, recently, a self-help group has started marketing their honey produced with branding as organic honey.

13.5 Site-Specific Afforestation/Agroforestry Systems for Coastal Saline Areas

On the coastlines wherever sulphur-containing sediments accumulate in tidal marshes or swamps or mangrove ecosystems, acid sulphate soil formation takes place. These formations are quite frequent in southern India and Andaman-Nicobar Islands. Under such conditions, soil also suffers from an excess of water-soluble iron and particularly of aluminium, and a toxic effect of these is a consequence of the strongly acidic pH. The application of lime mitigates the adverse and harmful effects on plants, but it is a costly proposition. Therefore, alternative land use systems need to be evolved. From the management purposes, the salinity-related problematic soils of the coastal areas may be classified as (i) land impregnated with high salinity and flooded with seawater, (ii) acid sulphate soils, (iii) land impregnated with high salinity and waterlogging but not flooded with seawater, (iv) land with low salinity and shallow water table (at 0.5–4.0 m depth) with good quality water but saline water beneath and (v) waterlogged and saline soils caused by seepage in canal command areas. Suitable agroforestry systems offer scope for increasing the income and employment generation for small farmers, meeting the local needs of fodder and fuel, conserving biodiversity, improving the coastal environment, protecting the soil from erosion and creating an environment for the wildlife. Some of the site-specific afforestation and agroforestry practices being followed are described here.

13.5.1 Afforestation of Land Impregnated with High Salinity and Flooded with Seawater

The areas lying closer to the sea are flooded regularly with seawater and, therefore, have high salinity. The tidal areas protected against high wind velocity and waves of high intensity (as in the case of many creeks, lagoons and estuaries) form a suitable situation for the cultivation of mangroves. For the cultivation of mangroves, we need seedlings of appropriate size. Many mangrove genera such as *Rhizophora*, *Ceriops*, *Aegialitis*, *Aegiceras*, *Bruguiera*, *Kandelia* and *Camptostemon* are viviparous in nature, and seed germinates when the fruit is intact to branch. The radical falls when mature and develops roots when it touches the muddy substratum. These mature radicals can be collected from the mangrove stands and planted directly in mangrove habitats or along protected shores as nursery in polybags. When seedlings are of the proper size, these may be planted directly in the tidal zone.

While planting the mangrove seedlings, the distance between the rows and seedlings may be maintained at 1.0–1.5 m. After 10–15 rows, a gap of 8–10 m may be left for future forestry operations. The zonation pattern may help in selection of species for a particular situation. It was advocated (Dagar 1982: Dagar et al. 1991; Dagar and Minhas 2016) that species of *Rhizophora* may be planted facing the sea followed by belts of *Bruguiera*, *Kandelia*, *Ceriops*, *Avicennia*, *Sonneratia* and *Excoecaria* in the middle zone towards land and species of *Ceriops*, *Aegiceras* and *Aegialitis* grown towards the border with associate mangroves such as *Thespesia populnea*, *Pongamia pinnata*, *Terminalia catappa* and *Calophyllum inophyllum*. Species such as *Rhizophora mucronata*, *R. apiculata*, *Avicennia marina*, *A. officinalis*, *Bruguiera gymnorrhiza* and *B. parviflora* prefer sandy clay substratum and can be grown in highly saline substratum, while species such as *R. stylosa*, *Ceriops tagal*, *Aegiceras corniculatum* and *Sonneratia alba* are found more predominantly on silty clay substratum usually found in the middle zone. *Sonneratia caseolaris*, *Xylocarpus granatum* and *Excoecaria agallocha* prefer low salinity and silty substratum and found distributed towards land. *Avicennia marina* is most tolerant to biotic stress and may be planted widely in all kinds of mangrove habitats. *Nypa fruticans*, a mangrove palm, is more predominant in muddy substratum along creeks. This can be propagated from suckers. *Terminalia catappa* (coastal almond), *Pandanus* spp., *Calophyllum inophyllum*, *Salvadora persica* and *Pongamia pinnata* are useful oil-yielding trees and can be commercially explored in areas bordering mangroves, but their nursery cannot be raised in the tidal zone. The alcohol-yielding *Nypa fruticans* is more frequent in muddy creeks of Andamans and Sunderbans and may be cultivated as a commercial crop.

Some denuded areas have been rehabilitated with suitable mangrove species along Goa and Tamil Nadu coasts of India. The sandy beaches along Orissa coast have been planted successfully with *Casuarina glauca*, *C. equisetifolia*, *Pandanus*, cashew (*Anacardium occidentale*), coconut and *Acacia auriculiformis* (Dagar 2014; Dagar and Minhas 2016). Due to a tsunami, land got elevated in North Andaman, and in many uplifted mangrove areas, due to non-availability of tidal water, mangroves have died and soils have turned acidic. Dam Roy and Krishnan (2005) reported a critical analysis of the effects of the tsunami in different locations of Andamans. *Avicennia marina* and *Sonneratia alba* were least affected showing their adaptability to cyclones. To rehabilitate the uplifted areas for the choice of species, we need careful analysis of soil and natural succession of vegetation. Species bordering mangroves such as *Clerodendr(on)um inerme*, *Thespesia populnea*, *Terminalia catappa*, *Salvadora persica*, *Casuarina glauca*, *Pandanus* spp. and *Pongamia pinnata* may find a place. *Salvadora persica* and *Salicornia* are useful oil yielding bushes and may be raised in highly saline swamps behind mangroves. In Rann of Kachchh area, *Salvadora persica* has been found a lifeline among many small farmers (Gururaja-Rao et al. 2000).

Several projects have been initiated for rehabilitation of mangroves in the Indian subcontinent, and a quite sizeable area has been planted with mangroves particularly in Korangi-Phitti creek and Indus Delta in Pakistan and Goa and Pichavaram in Tamil Nadu. Some denuded areas have been rehabilitated with suitable mangrove species along the Goa and Tamil Nadu coasts of India. The sandy beaches along

Orissa coast have been planted successfully with *Casuarina glauca*, *C. equisetifolia*, *Pandanus*, cashew (*Anacardium occidentale*), coconut and *Acacia auriculiformis*.

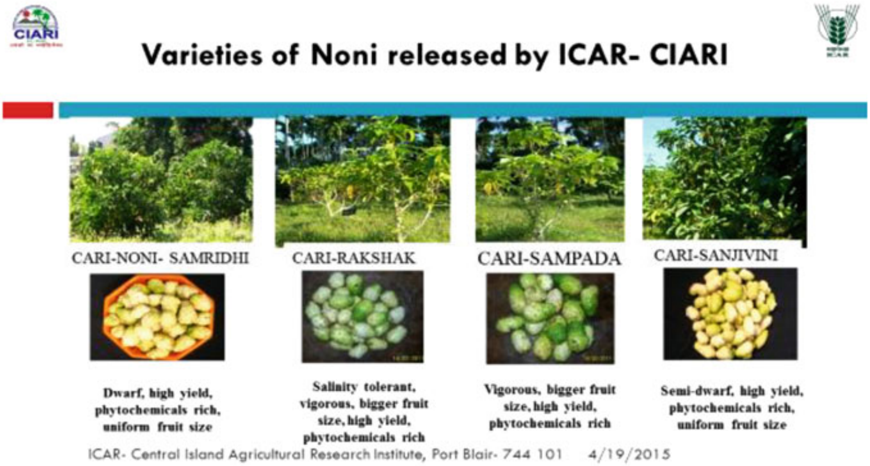
13.5.2 Rehabilitation of Acid Sulphate Soils

Most of these areas are reclaimed for rice cultivation. Coconut and Noni (*Morinda citrifolia*) have been found suitable for cultivation on raised (1–2 m) bunds (Fig. 13.12 for coconut; Fig. 13.15a for Noni) in areas inundated with seawater and also in other situations. Many varieties of Noni have been released by ICAR-CIARI (Fig. 13.15b). Noni is now a preferred tree in Bay islands because of its wider adaptability for different types of soils including waterlogging due to seawater inundation and its uses as a fruit (used as raw, pickle, juice, etc.) and foliage as fodder. In some rice fields, palmyrah palm (*Borassus flabellifer*), *Sesbania sesban*, *Gliricidia sepium* and *Casuarina* are found grown on bunds or as live fences. Lime application leads to high yield of rice, but more research attempts are needed for developing more salt-tolerant crops and improving sub-surface and surface drainage.

Besides coconut and Noni, other littoral MPTs along creeks and bunds of aquaculture ponds may be useful for the local rural population. In Andaman-Nicobar Islands and Kerala, coconut has been grown as a successful crop on reclaimed mangrove areas. Some varieties like Andaman Tall and Katchal Tall are doing well on raised bunds in brackish water yielding 19 nuts per palm (at soil ECe 22.5 dS m^{-1}) to 63 nuts per palm (at EC 11.4 dS m^{-1}) in a year. Areca nut is also frequently grown. Fodder species such as *Pennisetum purpureum*, *Tripsicum laxum* and *Panicum maximum* could be raised in interspaces of raised platforms yielding 20–34 Mg ha^{-1} forage in several cuts, and the channels could be utilized for fish culture (Dagar 1995). In some areas on bunds of rice fields, along with coconut, *Acacia auriculiformis*, *Sesbania sesban*, *Casuarina equisetifolia*, *Vitex negundo* and *Borassus flabellifer* palm are also grown. *Glircidia sepium* is a useful live fence in high-rainfall areas. In the low-lying acid sulphate areas of Southeast Asia, forest tree species such as *Casuarina junghuniana* and *Melaleuca leucadendron* are grown successfully and must be tried for Indian conditions which are almost similar.

Velmurugan et al. (2015) conducted experiments to assess the impact of bunding and broad bed and furrow (BBF) systems in restoring the productivity of inundated areas of South Andaman. They found that bunding of agricultural land leached out the salts by impounding rainwater with a significant reduction in electrical conductivity, sodium absorption ratio and exchangeable ions. The BBF system installed in low-lying waterlogged areas improved the drainage of the beds, harvested the rainwater (4476 m^3 ha^{-1}), prevented entry of tidal and runoff water into the furrow and reduced the overall salinity. In addition to it, microbial biomass C was significantly improved (193–210 mg kg^{-1} soil) and the soil under BBF systems adequately drained. Consequently, BBF systems enabled a higher cropping intensity (218%), increased fish productivity (INR 47.36 m^{-3}) and enhanced employment generation (213 man-days). Following this technology, farmers of Andamans could earn INR 117,532 per ha by growing vegetables, fruits, coconut and MPTs. Burman et al.

(A)



(B)

Fig. 13.15 (**a**) Noni (*Morinda citrifolia*) in the foreground, a useful multipurpose tree for islands which can be grown in a variety of situations (Photo courtesy Dr. I Jaisankar); (**b**) Varieties of Noni released by ICAR-CIARI

(2013) and Velmurugan et al. (2015) developed different land-shaping technologies in Sunderbans and Andamans for improving drainage facility, rainwater harvesting, salinity reduction and cultivation of plantation, crops and fish culture for livelihood and environmental security. For more details, see Dagar and Minhas (2016).

13.5.3 Afforestation of Land Impregnated with High Salinity but Not Flooded with Seawater

The area in Rann of Kuchchh along Gujarat coast comes under this category where due to excess of evapotranspiration salt accumulates on the surface. In some areas, MPTs such as *Salvadora persica*, *Tamarix articulata*, *T. troupii*, *Arthrocnemum indicum* and many halophytes are found growing naturally in these areas with stunted growth. *Prosopis juliflora* has spread as invasive species in most of the open degraded soils. Natural silvopastoral system is found with salt-tolerant forages such as species of *Kochia indica*, *Cressa cretica*, *Aeluropus lagopoides*, *Dichanthium annulatum*, *Leptochloa fusca* and *Sporobolus helvolus*. Gururaja-Rao et al. (2004, 2013) advocated that *Salvadora persica* can be cultivated on highly saline soils (ECe $>$ 55 dS m^{-1}). The plant started bearing seeds during the second year, and during the fifth year, it could produce 1838 kg seeds per ha. Fruit trees such as ber (*Ziziphus mauritiana*), pomegranate (*Punica granatum*), sapota (*Achras zapota*) and banana (*Musa paradisiaca*) could successfully be cultivated in saline black soil as well as coastal sandy saline soils of Gujarat. Many seed spices such as cumin, fennel, coriander, dill and fenugreek in isolation or with forest and fruit trees are suitable for saline black Vertic Haplustepts soils (Dagar and Tomar 1998; Gururaja-Rao et al. 2000, 2004, 2013). These may be irrigated with saline water.

A viable and productive silvopastoral system could be developed incorporating forage trees with suitable salt-tolerant forages such as species of *Atriplex*, *Kochia indica*, *Aeluropus lagopoides*, *Chloris gayana*, *C. barbata*, *Dichanthium annulatum*, *Leptochloa fusca*, *Echinochloa colonum* and *Sporobolus helvolus*. Oil-yielding species such as *Salvadora persica*, *Salicornia bigonie*, *Pongamia pinnata* and *Terminalia catappa* and firewood trees like *P. juliflora*, *Acacia nilotica* and *Casuarina glauca* could be raised in furrows and above-mentioned grasses in interspaces. In coastal sandy areas particularly along beaches of Orissa, *Casuarina equisetifolia* and cashew tree are successfully grown.

At many places, plantations of *Eucalyptus*, cashew nut (*Anacardium occidentalis*), soapnut (*Sapindus trifoliatus*), *Acacia leucophloea*, *A. auriculiformis* and *Tamarindus indica* are found grown successfully. The fodder species such as *Pennisetum purpureum*, *Panicum maximum*, *Brachiaria ruziziensis* and *Euchlaena mexicana* grown in association with *Casuarina equisetifolia* and *Ailanthus malabarica* recorded comparatively higher forage yield even after canopy formation in Kerala. These produced a biomass of 74.5, 59.0, 42.5 and 23.9 Mg ha^{-1}, respectively. Opportunities exist for growing salt-tolerant fodder trees in situations like wetlands of West Bengal. Forage grasses such as *Coix lacryma-jobi*, *Brachiaria mutica* and *Echinochlo*a spp. could successfully be cultivated producing 41.3, 31.1 and 24.4 Mg ha^{-1}, respectively, forage biomass from five cuts during the Kharif season (Biswas 1994).

In canal command areas of Karnataka, *Acacia nilotica* and *Casuarina equisetifolia* are found effective in controlling seepage along canals. The grasses in between complimented the effects. The water table receded significantly underneath the plantation and increased significantly outside the plantation area. Two to four rows of *A. nilotica* with a spacing of 4 m × 2 m parallel to the canal (5 m away from the canal) helped in canal seepage in Tug Bhadra irrigation command area (Vishwanath et al. 2013). Among other trees, *Acacia auriculiformis*, *A. ferruginea*, *Albizia lebbeck*, *Gliricidia sepium* and *C. equisetifolia* performed well under saline (ECe 10–12 dS m^{-1}) and high watertable conditions. Fruit trees Jamun (*Syzygium cuminii*) and sapota (*Achras zapota*) were better performers under shallow water table conditions.

13.5.4 Agroforestry on Waterlogged Saline Soils Caused by Intrusion of SeaWater

Eucalyptus is a fast-growing tree with a high transpiration rate and draws down the water table in waterlogged areas. Roy Chowdhury et al. (2011, 2012) conducted experiments in coastal deltaic Orissa where the problem of waterlogging was both due to seawater intrusion and topographical depression. They planted *Casuarina glauca* and *Eucalyptus camaldulensis* at two sites. *Casuarina* was also found to be more efficient in discharging saline groundwater; hence, it was used for bio-drainage plantation at the sites having more salinity. The effect of planted tree species on the underlain water table was monitored by them through observation wells and monitoring systems. The mean of the first two years (from April 2004 to March 2006) lowest water level at Patna (Orissa) was 102.0 cm below ground which declined to 117.7 cm in 3 years (i.e. from 2006–2007 to 2008–2009). Similarly, decline at Baghadi (Orissa) site was from 127.0 cm to 152.3 cm, at Alishibindha from 168.5 cm to 185.3 cm, and at Ambapada the decline was up to 150 cm. Thus, from the data, it was evident that at the phreatic surface, there has been a clear drawdown in the level of water table underneath bio-drainage vegetation.

This accelerated drainage by trees helped the farmer to advance *rabi* cultivation by a period of 15–20 days. Through this process, the cultivation of watermelon as an intercrop inside *Casuarina* vegetation could get additional benefit of about INR 15,000 per ha for the farmer due to better market price of the crop as well as avoiding the market glut. In the *Kharif* season, rice was taken as intercrop inside *Casuarina* vegetation at one site. The final average yield of the paddy obtained during 4 years was 1.75 Mg ha^{-1}. The yield under *Eucalyptus* ranged from 2.3 to 3.5 Mg ha^{-1} (average 2.6 Mg ha^{-1}) during the same period. At another site, the net return of watermelon under *Casuarina* plantation in *rabi* season was INR 30,000 (B:C ratio of 2.14). Similarly, under *Eucalyptus*, groundnut was cultivated and net return was INR 21,000 (B:C ratio 2.10), and from watermelon, net return was INR 62,500 (B:C ratio of 3.67). Aquaculture intervention in the bio-drainage field was also initiated during the first week of June 2007 using a dugout pond of 400 m^2 of water surface area at Baghadi along with *Casuarina* plantation. After carrying out standard pond preparation protocol, air-breathing fish like Magur (*Clarius batrachus*) and Koi (*Anabas testudineus*) were cultivated. A composite yield of 1.25 Mg ha^{-1} of fish was obtained within 10 months with a B:C ratio of 2.5.

Jena et al. (2006, 2011) modified the land by excavating ponds for storing excess water and created soil platforms for raising high transpiration trees such as *Acacia mangium* and *C. equisetifolia*. This land was highly acidic, low in organic carbon and available nutrients and high in iron contents. The growth of trees was far superior and remunerative in modified land configuration and helped in lowering down the water table for growing intercrops. Similarly, Mohanty et al. (2006) found the feasibility of growing cowpea (*Vigna unguiculata*) and turmeric (*Curcuma domestica*) intercrops with drip-irrigated banana plantation in a waterlogged situation where there were additional benefits from the turmeric irrigated by microtubes, and extension tubes were INR 24,700 and INR 24,200 ha^{-1} per season, respectively. Mohanty et al. (2004) reported that the storage of rainwater in ponds for developing aquaculture-based integrated farming systems involving fish, poultry and halophytic crops gave net returns of INR 69,000 ha^{-1} year^{-1} on 15 year-basis in Orissa. The horticultural plants included banana, papaya, pineapple, mango and areca nut. From another enterprise involving poultry, fish and plantation on dykes, they could get net returns of more than INR 200,000 per ha, and this enterprise was far superior to paddy-based or sugarcane-based and vegetable-based systems. Therefore, in coastal waterlogged areas, an integrated farming system is the most profitable and feasible approach. Thus, there lie many viable and profitable options in saline areas with sub-surface waterlogging.

13.5.5 Domestication of Halophytes as Agroforestry System

Halophytes are naturally evolved salt-tolerant plants which give optimum growth in a salt-rich environment where almost 99% of salt-sensitive species die because of NaCl toxicity and thus may be regarded as a source of potential new crops particularly for coastal areas where if necessary these may be irrigated with seawater (Dagar 2003; Dagar and Minhas 2016). While halophytes since long have been in the diet of the people and are utilized in a variety of ways in routine life, their scientific exploration as crops developed only in the latter half of the twentieth century (reviewed by Rozema et al. 2003; Panta et al. 2014; Dagar 2018). Species such as *Distichlis palmeri*, *Chenopodium quinoa*, *C. album, Plantago ovata, Pennisetum typhoides*, *Salicornia bigelovii*, *Diplotaxis tenuifolia* and several others have been established as food crops and are being explored commercially and can be cultivated using seawater for irrigation. Similarly, species of salt bushes *Atriplex*, *Salvadora* and *Maireana*; grasses *Leptochloa fusca*, *Chloris gayana*, *Aeluropus lagopoides*, *Brachiaria mutica*, *Panicum laevifolium* and *Paspalum conjugatum*; and many others are constituents of silvopastoral systems developed on waterlogged salt lands in different agroclimatic regions of the world. At least 50 species of seed bearing halophytes are potential sources of edible oil and proteins. *Salicornia bigelovii*, *Terminalia catappa*, *Suaeda moquinii*, *Kosteletzkya virginica*, *Batis maritima*, *Chenopodium glaucum*, *Crithmum maritimum* and *Zygophyllum album* are a few examples. A number of species including the halophytes *Tamarix chinensis*, *Phragmites australis*, *Spartina alterniflora* and species of *Miscanthus* have been evaluated as biofuel crops for ethanol production in the coastal zone of China (Liu et al. 2012), while many species such as *Halopyrum mucronatum*, *Desmostachya bipinnata*, *Phragmites karka*, *Leptochloa fusca*, *Typha domingensis* and *Panicum turgidum* are grown in coastal regions of Pakistan as a source of bioethanol (Abideen et al. 2011). In addition, several cultivars of sugar beet (*Beta vulgaris*), mangrove palm (*Nypa fruticans*) and kallar grass (*Leptochloa fusca*) are identified as a source of liquid and gaseous fuel (Jaradat 2003). Nypa palm has also been explored as alcohol-yielding species and is predominant in Sunderbans and Andamans. Screw pine (*Pandanus fascicularis*), quite predominant along the Indian coast, is rich in methyl ether of beta-phenylethyl alcohol and is used as a perfume and flavouring ingredient (Dutta et al. 1983). Many woody and succulent halophytes are used for turf production for golf and landscape development, paper industry, medicinal use and other commercial purposes. As stated earlier, mangroves are unique resources for the tidal zone, which must be protected and multiplied in mangrove-denuded areas. Therefore, more efforts are needed to domesticate these useful resources, particularly in coastal areas in agroforestry mode.

13.6 Conclusions

The coastal and island areas are usually vulnerable to disasters like cyclones, tsunamis and other climate vagaries incurring heavy productivity losses and associated salinity and waterlogging problems due to intrusion of seawater. In the scenario of climate change, the problem is going to be more severe due to sea-level rise when many fertile areas will come under seawater inundation. These fragile and resource-poor areas also face several other socioeconomic constraints and thus, demand a holistic approach to increase their agricultural productivity. Opportunities exist because of the rich biodiversity and high availability of rainwater (>1000 mm) and thus, paving the way for agroforestry-based strategies. The site-specific farming systems can combine forest and fruit trees, plantation crops, spices, forages, vegetables and halophytic plants. Integrated farming systems involving fish, shrimps, different kinds of aquaculture, multi-storey plantation-based cropping systems, duck- and chick-based poultry and high-value medicinal and aromatic plants and spices can be highly remunerative. In low-lying areas, land shaping has helped in utilizing salt-affected waterlogged areas for increasing farm productivity; hence, such programs must be undertaken at a larger scale with the support of different agencies involved in agriculture.

Mangroves are unique ecosystems which are nursery ground of several aquatic species, which stand a scope of commercial exploration through all kinds of aquaculture keeping mangroves intact. These will not only act as a life-support system but also protect the shores from natural disasters and act as a carbon sink. Priority must be to restore the denuded mangrove areas by planting suitable and profitable species of both mangroves and associate-mangroves. Thus, afforestation and agroforestry land use systems should be of great relevance to the coastal and island ecologies particularly in the scenario of climate change. Research efforts are needed in developing and domestication of high-value halophytic woody and herbaceous species. In coastal saline areas, leguminous species such as *Vigna marina*, *Clitorea ternatia* and *Canavalea* spp. are found natural giving room to develop stress-tolerant pulses by inculcating the potential genes. Many other wild relatives of fruit and spice trees and orchids may be utilized for developing disease-resistant high-value crops. Seaweeds and marine wealth can successfully be explored in food, cosmetic, fertilizer and drug industries. Many ornamental fish species can be explored for ecotourism. Thus, though vulnerable to climate change and other natural disasters, the coastal and island regions have tremendous opportunities for increasing agricultural and related productivity through integrated farming systems involving agroforestry interventions.

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Incentivizing Hill Farmers for Promoting Agroforestry as an Alternative to Shifting Cultivation in Northeast India

14

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Abstract

Northeast India (NEI) falls in the Indo-Burma biodiversity hotspot, which is one of the biodiversity hotspots of the world, that covers 17.2 million ha of land under forests, constituting ~25% of India's total forest area. Hill farmers in NEI are represented by over 100 different indigenous communities practising shifting cultivation for millennia in this biodiversity hotspot. Shifting cultivation, involving slash-and-burn agriculture, is one of the predominant land use systems in NEI and an important driver of soil degradation and greenhouse gas (GHG) emission. This work aims to contribute to better understanding of the system and provide decision-makers with alternative management options. Therefore, the specific objectives of this chapter are to (1) quantify tree diversity, biomass, and soil carbon dynamics in slash-and-burn agriculture, (2) assess ecosystem disservices caused by slash-and-burn agriculture, and (3) identify best alternatives to restore degraded land under slash-and-burn agriculture. We find that shifting cultivation is an important element of the cultural identity of indigenous communities of NEI. However, the shortened fallow cycle as practised currently is not ecologically sustainable and economically viable. We also find that slash-and-

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burn lands can be transformed into sustainable agroecosystems if best management practices such as agroforestry systems are widely promoted through appropriate incentive schemes. We propose developing appropriate cash incentive mechanism as a part of payment for ecosystem services for adoption and promotion of agroforestry systems in degraded slash-and-burn landscapes.

Keywords

Cash incentive · Land degradation · Land restoration · Short fallow · Tenure right

14.1 Introduction

Land degradation caused by soil erosion and poor land management is central to the interconnections and feedbacks addressed by the three "Rio Conventions" (United Nations Framework Convention on Climate Change, Convention on Biological Diversity, and United Nations Convention to Combat Desertification). At the September 2014 United Nations Climate Summit, governments rallied around an international agreement that underscored restoration of degraded ecosystems as an auspicious solution to climate change. As a follow-up, globally restoration of 350 million hectares of degraded lands by 2030 was committed by all the parties (Suding et al. 2015). However, achieving this promise requires careful thought about ecosystem restoration (Shackelford et al. 2013). Sustainable land management (SLM) is commonly considered as the main approach to prevent, mitigate, and reverse land degradation. Although the principles and practices of SLM are well known and SLM has been widely promoted through many land use projects in different countries, land degradation is growing to become a major global threat (Kust et al. 2017).

Geographically, Northeast India (NEI) is situated at the confluence of the Indo-Chinese, Indo-Malayan, and Indian biogeographical realms and represents numerous forest types falling within one of the biodiversity hotspots of the world, the Indo-Burma biodiversity hotspot (Mittermeier et al. 2004). In NEI, 17.2 million ha of land is covered with forests, which constitutes ~25% of India's total forest area (Roy et al. 2012).

Large-scale deforestation and shifting cultivation is the prime cause of soil degradation in NEI. Being the oldest farming system of the world and representing the dominant land use in the mountainous regions of South and Southeast Asia, hill farmers in NEI are represented by over 100 different tribes practising shifting cultivation for millennia. Shifting cultivation (also called swidden and slash-and-burn agriculture) is an agricultural practice that involves long fallow periods followed by slash-and-burn agriculture that allow soil fertility to recover after 1–2 years of agriculture. It is characteristic of the nutrient-poor soils of tropical forests, where cultivated lands may require years or decades to become agriculturally productive again (Teegalapalli and Datta 2016). This agricultural practice has evolved as a part of the culture of the hill people of the region, and the agricultural practices are closely linked with the sociocultural practices and religious beliefs. In NEI, the annual losses under shifting cultivation have been estimated at

(Mg ha^{-1} year^{-1}): 56.9 of top soil, 7.1 nitrogen (N), and 4 potassium (K) (Saha et al. 2012). Soil erosion, nutrient loss, and other ecosystem disservices exacerbated from cultivation with short fallows are jeopardizing the soil resilience and leading to poverty and food insecurity among the shifting cultivators (Nath et al. 2016). The work of the Nagaland Empowerment of People through Economic Development (NEPED) project and the International Centre for Integrated Mountain Development (ICIMOD) in Northeast India, Bhutan, and Nepal has suggested more research is necessary to understand how the shifting cultivation policies of governments can be more supportive in addressing the needs of shifting cultivators.

Considering the importance of the problem and in order to improve the livelihoods of the people, eradicate poverty, and stop the degradation of land, the National Institute for Transforming India (NITI) Aayog, Government of India in 2018 constituted a thematic Working Group on "Shifting Cultivation: Towards a Transformation Approach". The NITI Aayog also suggested five action points: (1) consolidate the learning on magnitude of the problem, (2) identify viable best practices with potential for upscaling, (3) assess institutions and need for transformation, (4) ascertain to what extent and which "co-benefits" could be delivered, and (5) suggest an action agenda (short, medium, and long term). In the present contribution, we will emphasize on the second action plan of NITI Aayog on identifying best management practices (BMPs) which is ecologically sustainable, economically viable, and socially acceptable. This work aims to contribute to better understanding of the system and provide decision-makers with alternative management options. Therefore, the specific objectives of this paper are to (1) quantify tree diversity, biomass, and soil carbon dynamics in slash-and-burn agriculture, (2) assess ecosystem disservices caused by slash-and-burn agriculture, and (3) identify BMPs including traditional and new agroforestry practices to restore degraded land under slash-and-burn agriculture. The NEI region is home to a diversity of traditional agroforestry practices, which are accepted as sustainable land management systems adopted by the mountain communities (Sharma et al. 2007). However, these remain little known to the outside world.

In order to fill the knowledge gaps, we present a synthesis of detailed studies on tree species diversity, soil and vegetation organic carbon dynamics, and sequestration potential under different fallow lands and compared the data to nearby native forests from Northeast India. We believe this comparative analysis will create a better understanding and awareness of the threats of current practices to the sustainability of the system among researchers, development agencies, and policy makers.

14.2 Extent of Shifting Cultivation in Northeast India

Shifting cultivation is practised in all of the NEI states except Sikkim. NEI consists of eight different states: Assam, Arunachal Pradesh, Mizoram, Meghalaya, Manipur, Nagaland, Sikkim, and Tripura. The area of shifting cultivation covers 26.3 million ha equivalent to 8% of the total geographical area of India (329 M ha). Some recent studies have shown that on an average, 44–55 km^2 of forest in Manipur (Thong et al.

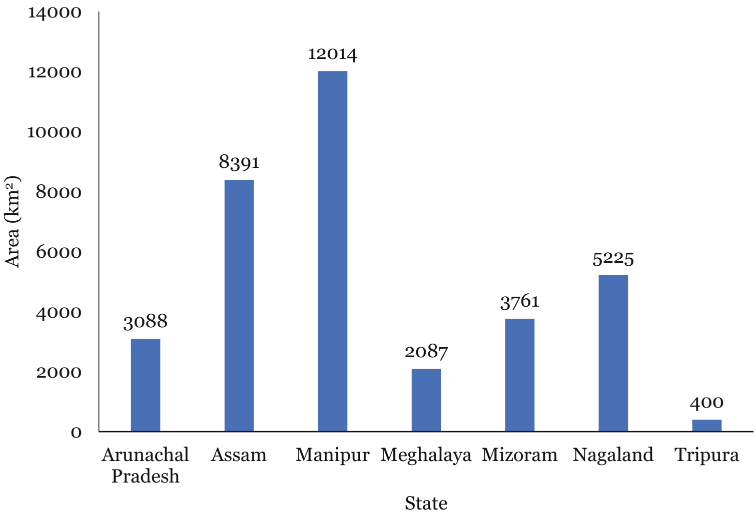

Fig. 14.1 Extent of shifting cultivated area under different states in NEI in 2000 (Source: Data of the Indian Council of Forestry Research and Education published in Statistical Year Book 2014 by MoSPI)

2019) and 114.46 km^2 in Mizoram (Thong et al. 2018) are annually slashed for shifting cultivation. According to data from the Indian Council of Forestry Research and Education (ICFRE), the largest land area under shifting cultivation is in Manipur and Assam state of NEI (Fig. 14.1). The *Statistical Year Book 2014* by the Ministry of Statistics and Programme Implementation (MoSPI) suggests significant reduction in the area under shifting cultivation over the last decade (2000–2010). The Wastelands Atlas Map 2014 shows around 50% reduction in shifting cultivation in NEI states from 16435.18 km^2 to 8771.62 km^2 in 2 years. Such a drastic reduction in a very short period may not be feasible. Therefore, data published by various agencies raises serious concerns regarding the accuracy and veracity of figures and need for urgently generating authentic data and/or reliable estimates for the current area under shifting cultivation on a decadal time series basis (NITI Aayog 2018).

14.3 Plant Diversity and Carbon Stock in Fallow Lands

The clearing of tropical rainforests is causing species loss at a rate unprecedented in the history of the earth (Wilson 1992). A comprehensive study describing changes in tree diversity, soil organic carbon and vegetation carbon dynamics, and organic carbon sequestration under fallow lands following shifting cultivation is lacking. A limited number of study suggests a gradual increase in diversity of woody species with time after abandonment of fallows (Lawrence 2004; Thong et al. 2016). For example, Lawrence (2004) reported a decline in species diversity from 25 to 10 species in 750 m^2 area following abandonment of shifting cultivation. Some studies also indicate recovery of ecosystem attributes after 50 years. However, species diversity and composition in secondary forests remain distinct from primary forest (Lugo 1992; Zou et al. 1995).

14.3.1 Fallow Management, Tree Density, and Tree Diversity

Our study revealed with increase in fallow age, tree density increased from 211 trees ha^{-1} under a 5-year-old fallow to 327 trees ha^{-1} under a 10-year-old fallow. However, tree density under a 10-year-old fallow was 68% lower than that under native forests (1055 trees ha^{-1}) (Table 14.1). Similarly, the basal area also increased with fallow age from 4.50 m^2 ha^{-1} under a 5-year-old fallow to 6.32 m^2 ha^{-1} under a 10-year-old fallow. The basal area under a 10-year-old fallow was 83% lower than that under native forests (37.31 m^2 ha^{-1}) (Table 14.1). The Shannon's Diversity Index (H) and Margalef's Species Richness Index (SRI) showed lower values under 5-year-old fallows ($H = 2.89$ and SRI = 5.69) and increased values under a 10-year-old fallow ($H = 3.22$ and 6.91). Shannon's Diversity Index (3.38) and Margalef's Species Richness Index (8.11) were highest under native forests (Table 14.1).

14.3.2 Fallow Management and Soil Organic Carbon Dynamics

Organic carbon in soil under a 5-year-old fallow in different soil depths was found to be lower than that under a 10-year-old fallow (Table 14.2). With respect to surface soil (0–20 cm), soil organic carbon (SOC) increased by 49% under a 10-year-old fallow than that under a 5-year-old fallow. However, SOC content in surface soil (0–20 cm) under a 10-year-old fallow was 212% lower than that under native forests (4.82%) (Table 14.2).

Analysis of SOC stock under fallow lands showed increases from 84.42 Mg ha^{-1} under a 5-year-old fallow to 106.37 Mg ha^{-1} under a 10-year-old fallow, with an annual increment of 4.4 Mg C ha^{-1} year^{-1}. In comparison to native forests, SOC

Table 14.1 Stand characteristics and tree species community indices in shifting cultivation fallows and native forests in Mizoram, Northeast India

Land use characteristics	Tree density (number ha^{-1})	Basal area (m^2 ha^{-1})	Shannon's Diversity Index (H′)	Margalef's Species Richness Index
5-year-old fallow	211 ± 16	4.50 ± 0.54	2.89 ± 0.09	5.69 ± 0.35
10-year-old fallow	327 ± 23	6.32 ± 0.84	3.22 ± 0.05	6.91 ± 0.31
Native forests	1053 ± 74	37.31 ± 3.87	3.38 ± 0.09	8.11 ± 0.74

Values are mean ± standard error. Data presented are based on five plots (0.1 ha) of a 5-year-old fallow, six plots (0.1 ha) of a 10-year-old fallow, and 6 quadrats of 0.1 ha of native forests.

Table 14.2 Soil organic carbon content (g kg^{-1}soil) and stock (Mg C ha^{-1}) under different fallow ages and native forests in Mizoram, Northeast India. Values are mean ± standard error

	SOC content (g kg^{-1}soil)			SOC stock (MgC ha^{-1})		
Soil depth (cm)	5-year-old fallow	10-year-old fallow	Native forests	5-year-old fallow	10-year-old fallow	Native forests
0–20	1.42 ± 0.04	2.12 ± 0.06	4.82 ± 0.08	22.70 ± 1.09	28.77 ± 1.41	45.31 ± 2.21
20–50	1.54 ± 0.04	1.67 ± 0.05	3.72 ± 0.06	27.52 ± 1.56	34.89 ± 1.94	38.0 ± 1.85
50–80	1.25 ± 0.05	1.42 ± 0.06	2.13 ± 0.07	22.37 ± 1.61	28.03 ± 1.97	32.05 ± 1.67
80–100	1.01 ± 0.03	1.14 ± 0.04	1.83 ± 0.05	11.83 ± 0.96	14.68 ± 1.13	20.87 ± 1.63

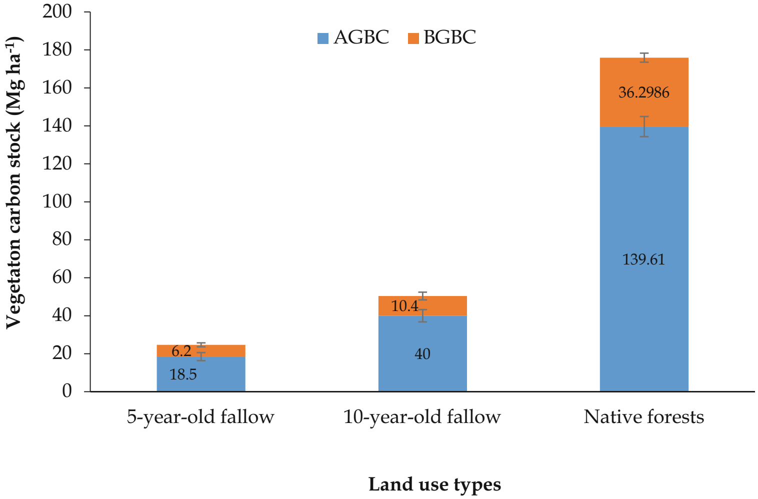

Fig. 14.2 Vegetation (above and below ground) carbon stock under different fallows and native forests of Mizoram state of Northeast India. Values are mean ± standard error. *AGBC* above-ground biomass carbon, *BGBC* below-ground biomass carbon

stocks under 5-year-old and 10-year-old fallows were 42% and 27% lower than that under native forests (146.23 Mg ha^{-1}), respectively.

14.3.3 Fallow Management and Biomass Carbon Dynamics

Total vegetation carbon stocks (above- and below-ground) increased from 24.7 Mg ha^{-1} in a 5-year-old fallow to 50 Mg ha^{-1} under a 10-year-old fallow with an annual accretion rate of 5 Mg C ha^{-1} year^{-1}. Vegetation carbon stock under natural forest was 176 Mg C ha^{-1}, which was 86% and 72% higher than that under 5-year-old and 10-year-old fallows, respectively (Fig. 14.2).

14.4 Ecosystem Disservices Provisioned by Short Fallow Management

Over the centuries, shifting agriculture has been sustainable with satisfactory yield on a long-term basis (Ramakrishnan 1992; Ziegler et al. 2009). The small-scale perturbations, in the past, ensured enhanced biological diversity in the forest, with enriched crop and associated biodiversity, capitalizing on the nutrient released through slash-and-burn (Ramakrishnan 2016). Under long fallow management (≥25 years), forests were able to recover and capable of sustaining 3–5-year continuous cropping after slash-and-burn (Fig. 14.3). With the increase in pressure on forest resources from outside and population pressure from within, there has been

Fig. 14.3 Schematic representation of long fallows and its role in improvement in biomass content and soil quality following shifting cultivation

declining soil fertility through land degradation, and agricultural/fallow cycle has shortened (Ramakrishnan 2016; Nath et al. 2016). With the reduction in fallow age to 3–5 years, shifting cultivation has accelerated soil erosion, nutrient loss, reduced system stability and resilience, decline in productivity, substantial carbon dioxide emission into the atmosphere, and reduction in biodiversity. All these environmental consequences ultimately exacerbate ecosystem disservices (Fig. 14.4) and can lead to irreversible degradation of soil and a disintegration of the ecosystem (Nath et al. 2015).

A global synthesis has shown soil erosion (60–80% more) and surface runoff (80–100% more) are more under short fallow than under native forest (Nath et al. 2016). Following slash-and-burn in forests, the ecosystem loses its ability to hold nutrients (Ramakrishnan 2016). Soil under short fallow is prone to a high nutrient loss (60–700% more than native forest), resulting in low agronomic yield (Ando et al. 2014). During the short fallow period, decline in soil structure is closely linked with a decrease in soil organic matter (SOM) and soil humus contents (Ziegler et al. 2009). Largely herbaceous vegetation that develops under short cycles of 3–5 years does not help in adequate SOM build-up to replenish the lost soil fertility (Ramakrishnan 2016). A decrease of 20% of SOC in top soil during the cropping

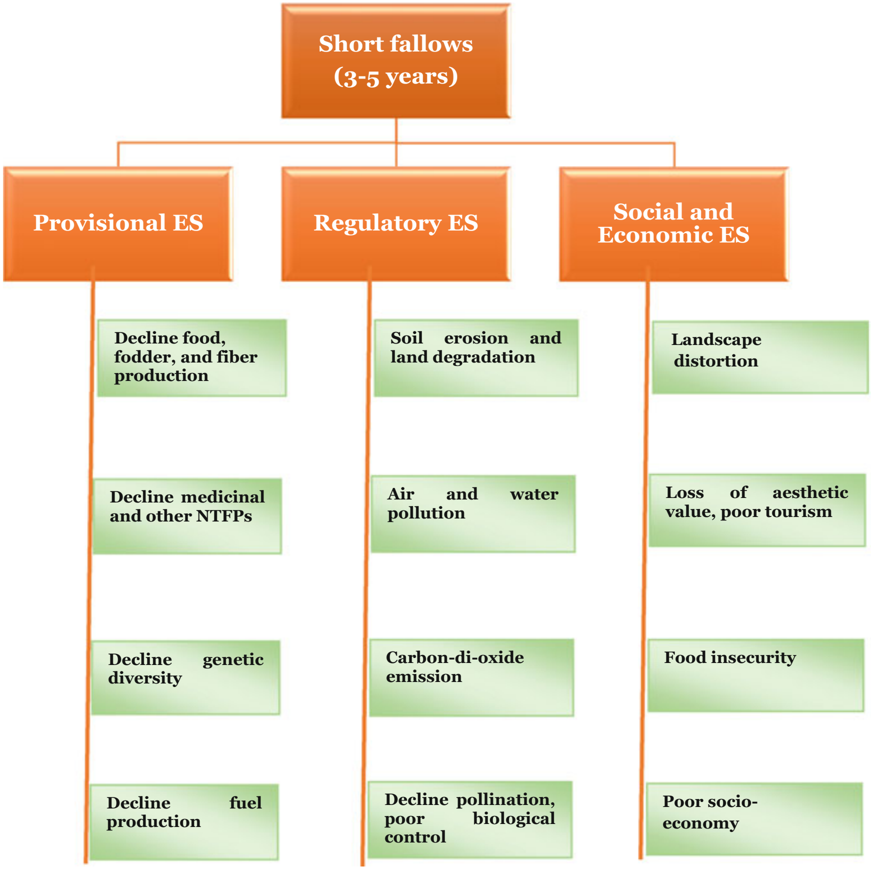

Fig. 14.4 Provisioning ecosystem services of short fallow management

phase of shifting cultivation has been reported (Bahr et al. 2014), and it may take up to 35 years to regain the content comparable to that under a primary forest (Palm et al. 1996). Therefore, sustainability of this age-old subsistence agricultural system is questionable in the era of anthropogenic climate change.

14.5 Agroforestry: A Transformative Practice for Shifting Cultivation

Development of site-specific and sustainable agroforestry models has been the most widely tried land use approaches to shift from slash-and-burn cultivation (Niti Aayog 2018). Nevertheless, socio-economic and cultural beliefs determine the acceptability of the alternative practices in these farming communities (Teegalapalli and Datta 2016). Tropical agroforestry systems have been found to be the most promising ways to conserve biodiversity and associated ecosystem services in crop production sectors (Steffan-Dewenter et al. 2007). The importance of these agroforestry systems has been realized to render several ecosystem services, i.e. food production, carbon sequestration, regulation of hydrological cycles, and minimization of soil erosion and sediment load (Lasco et al. 2014; Idol et al. 2011; Jose 2009; Alavalapati et al. 2004; Singh et al. 2014). The tangible benefits of trees grown on farmland include fire wood, fodder, timber, fruits, and medicines which help in income generation and poverty alleviation of farming communities (Tscharntke et al. 2011; McNeely and Schroth 2006). Studies on agroforestry systems in various parts of the world have found that the economic benefits in terms of net present value (NPV), internal rate of returns (IRR), benefit-cost (B/C) ratio, return to land or nature, and return to labour are much higher than seasonal agricultural practices (Ajayi et al. 2009; Roshetko et al. 2013; Rahman et al. 2008; Rasul and Thapa 2003). These benefits are found suitable especially in marginal land where other agricultural practices are economically less viable (Roshetko et al. 2008; Rahman et al. 2016). The combination of trees and shrubs with agricultural crops has been recognized the most sustainable farming system as an alternative land use type (Nair and Garrity 2012). Adoption of agroforestry practices helps in soil nutrient retention, increased soil quality, improved wildlife habitats, reduced fossil fuel use, and increasing resilience in the face of an uncertain agricultural future (Winans et al. 2015; Dixon et al. 1994; Jordan and Davis 2015). The facts described above strongly appeal the promotion of tree-based crop production models in slash-and-burn cultivation areas in NEI for sustaining mountain agro-biodiversity, forest cover, and soil carbon storage.

14.5.1 Alder-Based Traditional Agroforestry Systems

Himalayan alder (*Alnus nepalensis*) has commonly been used in traditional agroforestry systems as shade, fodder, fuelwood, and timber (Rana et al. 2018). These traditional agroforestry systems are unique in hilly regions of Nepal and adjoining Himalayan countries (Sharma et al. 2007). Himalayan alder-based agroforestry practised by Angami tribe in Khonoma Village, Kohima, in Nagaland is a popular traditional knowledge-based sustainable farming system in Eastern Himalaya. This farming system is both highly productive and protective of natural resources (Fig. 14.5). More than 100-year-old alder trees have been maintained by the farmers with indigenous knowledge-based innovative management systems. Himalayan alder is a non-legume tree species which fixes atmospheric nitrogen (N_2) in association with an *Actinobacteria* called *Frankia* sp.

Net litter production and addition of nitrogen in alder-based traditional agroforestry system varies with tree density and has been reported in the range of 60–625 trees ha^{-1} and that produces 3.37–13.56 Mg ha^{-1} litter and 48.3–184.8 kg ha^{-1} nitrogen in the soil (Rathore et al. 2010). In this farming system, mature and old alder trees are pollard at the height of 2–4 m above the ground, and leaves are burnt in the field before preparation of land for cultivation. The wood is collected and used for

Fig. 14.5 Traditional alder-based agroforestry system (**a**–**d**) in Nagaland state of Northeast India

firewood, timber, and charcoal making. In a recent study, Giri (2019) reported the SOC stock of 97 Mg ha^{-1} in the surface soil (0–30 cm) under alder-based systems. It was also reported the carbon sequestration rate in such systems is higher than slash-and-burn agriculture. In another study, Giri et al. (2018) reported that the soil under alder-based agroforestry system is highly fertile, productive, and rich in microbial population.

The available nitrogen and SOC content in the soil were observed to be 6.7 g kg^{-1} and 31.1 g kg^{-1}, respectively. Giri et al. (2018) also enumerated diversity of crops associated with this agroforestry system where the farming communities mainly grow vegetables such as potato, tomato, chilli, cabbage, cauliflower, squash, cucumber, ginger, French bean, soybean, pea, millet and maize, while the farmers of Khonoma village cultivate paddy in the wet terrace, which is one of the oldest terrace systems in Nagaland. The terrace system receives water from natural forests and alder-grown hill areas. Fertilization of paddy crop with this nutrient-rich water makes the system productive and sustainable. After harvesting paddy, crop residues are either allowed to decompose or burnt, and during gestation period, ginger, garlic, carrot, and other vegetables are grown in the terrace farmland. The farmers of this village have zero dependency on surrounding natural forests for their livelihood requirements. Therefore, alder-based agroforestry model of Angami tribes, which is a distinct form of shifting cultivation, is highly productive and sustainable which has conserved the natural biodiversity in the region. Agricultural crops, together with alder trees, form a very remunerative agroforestry system, and the ability of trees to develop and retain soil fertility has been fully utilized by the tribal farmers. Besides Angami farmers, Chakhesang, Chang, Yimchunger, and Konyak tribes of Nagaland have also adopted this farming system as a traditional practice in Nagaland (Kehie et al. 2017). This traditional agroforestry model has a tremendous potential to be replicated in other subtropical to temperate climatic regions of NEI as an alternative to slash-and-burn system.

14.5.2 Promotion of Traditional *Piper betle*-Based Agroforestry

Over the millennia, tribal community in NEI has evolved different traditional agroforestry systems to secure and upgrade their social and economic security. One such example is *Piper betle*-based agroforestry system in NEI. *P. betle* leaves are the most important plant part and are of medicinal, religious, and ceremonial value in Southeast Asia. The fresh leaves of *P. betle* are popularly known as paan in India, which are consumed by about 15–20 million people in the country (Guha 2006). *P. betle* cultivation is a traditional agroforestry system that involves slash-and-mulch instead of traditional slash-and-burn technique where the *P. betle* vines are grown along with the other tree species within the same field. In addition to economic benefits to the tribal communities, a recent study by Brahma et al. (2018) suggested that restoration of degraded lands in NEI through *P. betle*-based agroforestry enhanced ecosystem carbon sequestration rate and reduced CO_2 emissions from land use change. In NEI, *P. betle* cultivation is performed traditionally by the Khasi community, and its expansion to other tribal communities living in similar climatic condition can play an important role towards economic viability, environmental sustainability, and livelihood security of the tribal people of the NEI.

14.5.3 Fertilizer Tree-Based Potential Agroforestry Practices

Fertilizer trees are nitrogen-fixing perennials, including the legume (*Rhizobium*) and non-legume (*Frankia*) symbioses, that are used in agroforestry systems to provide various goods and services (Sileshi et al. 2014). There are a number of agroforestry practices which capitalize on biological nitrogen fixation (BNF) from fertilizer trees for the supply of N and organic matter to annual and perennial crops. These include alley cropping, improved fallows, cereal-tree legume intercropping, relay cropping, multistrata agroforestry, agroforestry parklands, and silvopastoral systems (Sileshi et al. 2014). Though the total nitrogen fixed by legume trees in the field is difficult to assess, approximate estimates ranging from 10 to 600 kg ha^{-1} year $^{-1}$ have been reported by La Rue and Patterson (1981), with variations due to species type and prevailing environmental conditions. Therefore, varieties of seasonal and perennial legume pulses are widely cultivated in agricultural land for soil fertility and crop productivity enhancement (Sileshi et al. 2014). Similarly, leguminous and actinorhizal trees have gained huge attention in agroforestry systems to harness their ability of atmospheric nitrogen fixation and soil fertilization. Nitrogen is often a limiting element in soils of humid tropics and shifting cultivation land. These nodule-forming plants fix significant amount of nitrogen within their roots and maintain fertility of soils (Franche et al. 2009).

The majority of nitrogen-fixing trees are pioneers, which can establish easily on poor or degraded sites. These tenacious trees also grow rapidly and produce large amounts of nitrogen-rich green foliage and make the soil fertile. *Bauhinia variegata*, *Bauhinia purpurea*, *Albizia lebbeck*, *Albizia procera*, and *Leucaena leucocephala* are grown in different parts of NEI. These trees have the ability to form root nodules induced by symbiotic *Rhizobium* species and soil fertilization potential. *Parkia timoriana* commonly known as tree bean is a multipurpose tree species found in Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, and Tripura. This tree is generally grown in semi-wild conditions or in homestead backyard gardens (Roy et al. 2016) and provides livelihood to the majority of village people in the region. The household monthly income from sale of pod only ranged from US $ 100 to 1200 during the harvesting season (Rocky et al. 2004). The flowers and tender pods of *Parkia* are eaten as vegetable in Manipur, Mizoram, and Nagaland states of NEI. However, it is more popular in Manipur than other states in NEI (Singh et al. 2009, 2010). Due to rich nutritional and medicinal properties, it is being cultivated by the rural tribal communities in slash-and-burn land and homesteads. Considering its socio-economic and environmental importance, it is highly suitable for agroforestry in slash-and-burn fields in Manipur and other parts of the NEI. *B. variegata*, *A. lebbeck*, *A. procera*, and *L. leucocephala* are the potential legume trees, which are suitable for agroforestry components to transform slash-and-burn paddy monoculture into diverse agroforestry system in the hill regions of NEI. *B. variegata* leaves, flowers, and fruits are used as vegetable, and the bark, dried buds, roots, and flowers are used as medicine. The tree is a quality fuelwood source in rural areas having 4800 kcal kg^{-1} calorific value (http://www.worldagroforestry.org/). This multipurpose tree species has a tremendous potential in slash-and-burn fallow management through agroforestry interventions in the tropics. *L. leucocephala* is another multipurpose tree which is used in restoration of degraded habitats. The foliage of *Leucaena* can be used as legume fodder for cattle, while the wood is often used as timber, paper pulp, and biofuel production (Ishihara et al. 2018). The multifarious uses of *Leucaena* tree make it a suitable agroforestry species in slash-and-burn cultivation management in NEI, while *C. fistula* widely grown as an ornamental plant in tropical and subtropical areas is a source of fuelwood. The leaves are used for dietary supplement of cattle, sheep, and goats fed with low-quality forages (Heuzé et al. 2018), while the seeds of this tree are used as medicine. Cultivation of fertilizer trees in degraded slash-and-burn lands can be a promising alternative for transformation of this land use system into an ecologically and economically viable and socially acceptable land use system (Fig. 14.6).

Introduction of shrubby species like *Cajanus cajan* (pigeon pea) in the shifting cultivated fields either as a component of the multiple crop or along the contours may

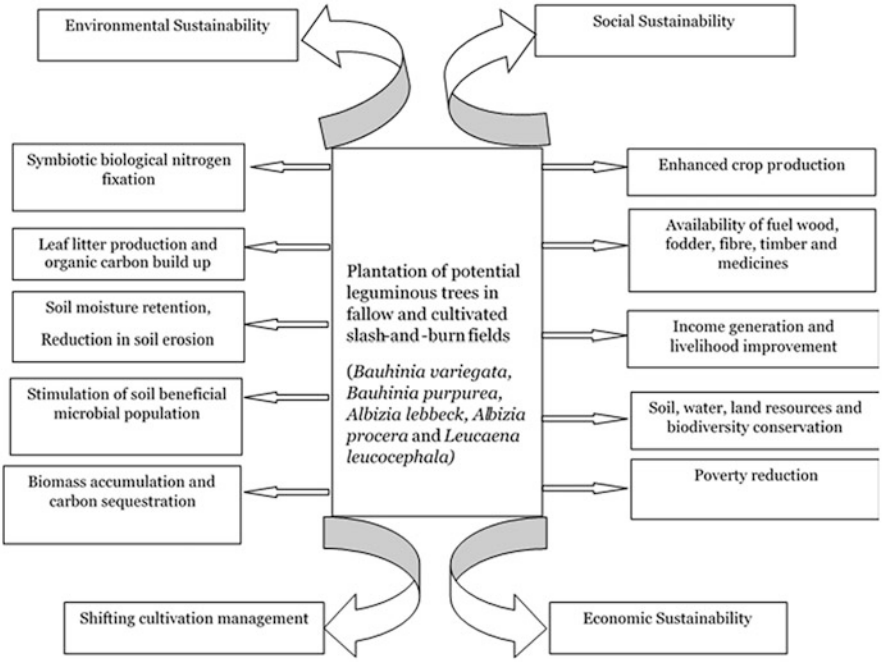

Fig. 14.6 Fertilizer tree-based agroforestry systems and its provisional ecosystem services

improve soil fertility and crop productivity. With this hypothesis, a study was under taken in shifting cultivated fields in Nagaland state of NEI where pigeon pea was grown as a component crop of mixed cropping system. It was observed that introduction of pigeon pea enhanced many of the soil physical and chemical properties (Table 14.3, Fig. 14.7). Productivity of paddy under mix cropping with pigeon pea produced higher yield (Table 14.3). The study suggests that introduction of soil-enriching legumes in cultivated slash-and-burn fields enhances soil health and improves crop productivity under short fallow cycle.

Many plants that grow widely in NEI have multiple uses such as medicine, food, fodder, manure, fuel, timber, handicrafts, and fibre. Commonly planted multipurpose tree species in NEI are *Gmelina arborea*, *Alnus nepalensis*, *Melia azedarach*, *Terminalia myriocarpa*, *Parkia timoriana*, *Toona ciliata*, *Aquilaria malaccensis*, *Duabanga grandiflora*, *Neolamarckia cadamba*, *Bombax ceiba*, *Artocarpus chaplasha*, *Bauhinia purpurea*, *Acrocarpus fraxinifolius*, *Magnolia champaca*, *Morus laevigata*, *Schima wallichii*, *Phoebe goalparensis*, *Cinnamomum zeylanicum*, *Cephalotaxus griffithii*, *Sterculia villosa*, *Wrightia tomentosa*, and *Zanthoxylum acanthopodium.* Adoption of multipurpose tree-based agroforestry models will provide short-term tangible and intangible benefits to the hill farming communities. However, accumulation of biomass and carbon, climate regulation, soil conservation, and hydrologic cycling are the long-term environmental benefits of multipurpose tree-based agroforestry systems.

Table 14.3 Comparison between soil nutrients, bacterial population, and crop productivity in *Cajanus cajan*-based slash-and-burn and traditional slash-and-burn management cultivation in Mokokchung, Nagaland, Northeast India

Parameters	Traditional slash-and-burn paddy field	*Cajanus cajan* slash-and-burn paddy field
pH	4.74 ± 0.09	5.14 ± 0.25
Organic carbon (%)	2.02 ± 0.20	3.38 ± 0.12
Organic matter (%)	3.48 ± 0.34	5.82 ± 0.21
Soil carbon density (Mg ha^{-1})	73.86 ± 5.78	97.44 ± 4.35
Available N (kg ha^{-1})	112.0 ± 8.60	284.0 ± 9.27
Available P (kg ha^{-1})	20.64 ± 0.89	31.13 ± 2.97
Exchangeable K (kg ha^{-1})	37.22 ± 2.73	63.03 ± 4.79
Colony Forming Units (CFU) per gram soil	414×10^6	693×10^6
Gene copy no (qPCR)	4.19×10^8	8.39×10^{10}
Crop productivity	**Year: 2015–2016**	**Year: 2016–2017**
Cajanus cajan paddy (kg ha^{-1})	3015.5 ± 30.5	Pineapple-tapioca-vegetables
Traditional paddy (kg ha^{-1})	1978.5 ± 16.5	1624.0 ± 16.0

Values are mean ± standard error, n=10

(a) (b)

Fig. 14.7 (**a**) A shifting cultivated landscape and (**b**) *Cajanus cajan*-based slash-and-burn cultivation system in Nagaland state of Northeast India

14.6 Incentivizing Agroforestry Systems

The adaptation and GHG mitigation potentials of agroforestry have attracted significant interest in carbon credits under the Verified Carbon Standards and Reduced Emissions from Deforestation and Forest Degradation (REDD+) programmes. 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. Policies and practices trying to address problems associated with shifting cultivation may benefit from the provisions of such schemes. Considering the deteriorating socio-economic situation of communities in NEI, consequences of land degradation, and other ecosystem disservices from shifting cultivation, it is important that land under shifting cultivation is restored and further land degradation is prevented.

This may be achieved through incentive schemes for farmers to transition from shifting cultivation to more sustainable land use practices. For example, farmers may be provided with cash incentive as a part of payment for ecosystem services (PES) for adopting agroforestry practices. Rather than a subsidy, cash incentive will be a kind of PES for hill farmers' participation in restoration of degraded fallow lands. This can be based on successful models in the region. For instance, under Sustainable Land Management Program in Bhutan, cash incentives (approximately USD 121, per ha) were given to the hill farmers for converting their shifting cultivation lands into terraced dryland (Phuntsho et al. 2015). So far, the project has converted more than 4500 acres (1821 ha) of shifting cultivation lands into terraced dryland. Therefore, opportunity exists to scale cash incentive-based mechanism to involve hill farmers in restoration of degraded fallow lands in NEI.

Carbon (C) farming is also rapidly becoming the new agriculture where C sequestered in soil/trees could be traded just as any other farm produce. Three mechanisms of compensating farmers are already in operation: (1) C credits based on cap and trade, (2) C maintenance fees, and (3) payments for ecosystem services. All three mechanisms consider the inherent value of soil C. Therefore, adoption and promotion of agroforestry systems on degraded fallow land will accelerate the C sequestration process in soil and vegetation, and the C stored in the ecosystem can be traded under national and international C market schemes. The "Grain for Ecosystem Carbon Management" approach (Nath et al. 2016) can also be a good model to promote agroforestry and restoration of degraded fallow lands in NEI. The ecological and socio-economic incentives for promoting agroforestry include land restoration, food security, and increased household incomes through PES.

14.7 Conclusions and Recommendations

Shifting cultivation is an important element of cultural identity of ethnic communities of NEI. However, the shortened fallow cycle as practised in most places in NEI is not sustainable. Therefore, these systems need to be transformed into sustainable agroecosystems through the promotion of appropriate agroforestry practices and soil and water management structures.

In few selected areas where fallows are relatively longer (as in Ukhrul and Chandel district of Manipur) and some parts of Nagaland, rotational shifting cultivation is still an appropriate land use and should be supported by the local government through accelerated allocation of agricultural and forest lands to the farmers with secured tenure. Retention of useful species and fallow enrichment with suitable perennials and fruit, and forest trees, or bamboo and rattan in such traditional long fallow would increase the diversity of income to the shifting cultivators.

Despite the importance of women in shifting cultivation, they are discriminated against and often lack property rights and access to productive resources. Deliberate policy efforts are needed to guarantee land rights for women members who are also the prime part of shifting cultivation since millennia. Additionally, improving the social status of hill farmers through state and central government legislation can enhance their role in adoption and promotion of agroforestry systems. However, adoption of agroforestry and investment in land rehabilitation requires land rights and security of tenure. This will enable them to access credit, inputs, and extension services to facilitate adoption and promotion of agroforestry systems as an alternative to shifting cultivation. Developing appropriate cash incentive-based mechanism for adoption and promotion of agroforestry systems in degraded fallow lands in NEI may promote its acceptability among the hill farmers.

Additionally, to achieve the goal of (1) "The Shillong Declaration" on shifting cultivation in the Eastern Himalayas and (2) "National Mission for a Green India" under the National Action Plan on Climate Change 2011, the proposed cash incentive protocol for restoration of degraded fallow ecosystems of NEI may be a viable option. This strategy will provide multiple benefits in social, ecological, and economic aspects, viz. (1) achieving United Nations proposed programme of land degradation neutrality or zero net land degradation, (2) promoting the United Nations sustainable development goals (SDGs) of poverty alleviation by involving the hill farmers in restoration programmes and securing their earnings through PES, and (3) restoring ecosystem carbon for critical ecosystem functions and services. Therefore, successful implementation of cash incentive for promotion of agroforestry system as an alternative to shifting cultivation in NEI will be a triple-win option.

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The Contribution of Agroforestry to Restoration and Conservation: Biodiversity Islands in Degraded Landscapes

15

Florencia Montagnini

Abstract

Biodiversity islands can contribute to protect biodiversity in human-dominated landscapes. Agroforestry systems (AFS), as they can harmonize productivity with environmental functions, can be part of biodiversity islands, especially in the buffer zones of protected areas. AFS are heterogeneous in their design and management, with consequences for their restoration and conservation functions. This chapter discusses the role of AFS on restoration and conservation of biodiversity at the ecosystem and landscape levels, with emphasis on tropical Latin America and examples from other regions.

Multistrata AFS of home gardens and successional agroforestry hold the largest biodiversity. Home gardens can be as diverse in humid as in dry ecosystems as people in poorer areas take special care of these AFS that provide for their subsistence. Home gardens are rich in genetic resources as people domesticate preferred native species, and they are also sites for conservation of species that are only found in these AFS, while they have been extirpated from the wild. Development projects are currently working with farmers in identifying lesser known species of fruits and medicinals and other species from home gardens, helping farmers in nursery establishment as well as reaching specialized markets. Both traditional and modern successional AFS combine restoration and biodiversity objectives.

Perennial crops under shade (coffee, cacao, yerba mate) exist in a range from traditional multistrata assemblages to more simple designs with fewer tree species, and their function in biodiversity conservation varies accordingly. Differential prices paid for organic/biodiversity-friendly products from AFS may act as incentives for promotion of agroforestry-based systems.

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Diversity of birds, arthropods, and other fauna is greater in silvopastoral systems (SPS) than in conventional pastures. Tree cover is the main factor associated with diversity in SPS, and a compromise must be found to reach cover that sustains biodiversity while not decreasing productivity. Recent research and development of SPS has resulted in more complex designs such as the intensive SPS (ISPS) which use agroecological principles resulting in more productive and environmentally friendly systems. Payments for environmental services (PES) have been successful in Latin America to promote SPS and ISPS, including planting more native trees (focal species).

Living fences and windbreaks are often the only arboreal component in agricultural landscapes, and they serve roles in connectivity among forest patches. Adding more complexity to these linear systems contributes to their biodiversity value, but it may compromise their utilitarian functions. Recommendations are given to use AFS designs and practices to favor biodiversity and their inclusion as part of biodiversity islands.

Keywords

Buffer zones · Certification · Connectivity · Human-modified landscapes · Markets · Organic farming · Payments for environmental services

15.1 Introduction

Sustainable agricultural management techniques geared to harmonizing ecosystem productivity and conservation can contribute to mitigating or reversing detrimental effects on landscapes. Agroforestry systems (AFS), which combine trees and crops on the same land, including silvopastoral systems (SPS), the combination of trees and pastures/cattle in the same production unit, can increase productivity in the short and long term. They are also biodiversity friendly and bring social and economic advantages to the farmer (Montagnini and Metzel 2017). Due to their capacity for harmonizing production with environmental values such as biodiversity conservation, AFS are often important components among land uses in buffer zones of protected areas. Thus, AFS can be a great tool as component parts of biodiversity islands.

Traditional as well as more modern multistrata AFS such as home gardens and successional agroforestry designs provide households with food sources and fuelwood, as well as high-value products to generate cash income (Kumar and Nair 2006; Montagnini 2006; Montagnini and Metzel 2015). Perennial crops such as cacao, coffee, and yerba mate gain considerable advantage in terms of quality of products and system sustainability when grown in AFS. In addition, when designed and managed as organic farming, AFS yield products which can obtain more favorable market prices (Eibl et al. 2015; Rapidel et al. 2015; Virginio Filho et al. 2015). Organic AFS are also more biodiversity friendly as lack of pesticide and herbicide use will favor both plant and animal diversities (Montagnini et al. 2011; Rossi et al. 2011).

Silvopastoral systems, when properly designed and managed, can provide short-term income from cattle products as well as long-term returns from the trees, helping diversify investments while providing a full set of environmental benefits and services, including carbon sequestration and biodiversity (Murgueitio et al. 2011; Chará et al. 2015). Live fences, windbreaks, and riparian buffer strips contribute to provide connectivity to fragmented agricultural landscapes (Francesconi et al. 2011a, b; Francesconi and Montagnini 2015).

The role of AFS in decreasing deforestation is an additional contribution to biodiversity conservation. More than 80% of rural people in the developing world still depend on fuelwood for cooking as well as warmth (Angelsen et al. 2014; FAO 2015). AFS can play a role in supplying fuelwood energy and facilitating the provision of other sources of energy, thus avoiding forest cutting for fuelwood (Marlay 2015; Berg 2017).

With the current need to supply food and resources to a growing and expanding human population, the advance of the agricultural frontier and the fragmentation of the landscapes call for urgent measures to preserve biodiversity (Montagnini and Berg 2019). A biodiversity island is an area of protected ecosystem in a human-dominated landscape or region. Biodiversity islands help saving sections of land where plants and animals can thrive without major degenerative interference from human activity (Montagnini and Berg 2019; Montagnini et al. 2020). Building upon foundations of island biogeography, biodiversity islands act as ecological refugia, protected areas, or reserves within the landscape, protecting a multitude of plant and animal species for present and future generations (MacArthur and Wilson 1967; Tjørve 2010). Biodiversity islands' size, configuration, and position in the landscape may vary according to various guidelines as well as by patterns of human settlement, development, and utilization of natural resources (Laurance 2008). Biodiversity islands may include a buffer zone to transition from areas of greater human impact or degradation. Multiple biodiversity islands which spread over a large area in an optimal configuration can decrease chances of biodiversity loss through creation of repopulation reserves and biological corridors (Harvey et al. 2008).

The specific characteristics of each AFS vary strongly according to system design, objectives, and species involved. There are strong differences in AFS design and practices within and between ecological regions. Countries and locations can influence these practices, along with their productivity, sustainability, and environmental services, all depending on the interaction of economic, social, and political factors which are predominant in each case (Montagnini and Metzel 2017). Therefore, functions of AFS, including their role in biodiversity conservation and restoration, can vary widely. Caution should be taken when deciding on design and management of AFS to be included in the landscape. For example, AFS promotion may be used as part of an argument to justify forest cutting and advance of the agricultural frontier, claiming that AFS can have a strong role in restoring or preserving biodiversity. Rather, AFS can compensate for biodiversity loss, helping to restore and preserve biodiversity in regions where the landscape has already been converted to agriculture, and there are also areas of degraded land that need to be restored. The same caution should be taken when planning and designing AFS as component parts of biodiversity islands.

This chapter offers a review of studies of restoration and conservation of biodiversity in AFS at both the ecosystem and landscape levels. As biodiversity in AFS varies strongly according to system characteristics, the next section discusses the role of the most frequent AFS, multistrata systems, including home gardens and successional AFS, perennial crops under shade, silvopastoral systems, living fences, and windbreaks. The chapter ends providing recommendations on how to use AFS as components of biodiversity islands in human-dominated landscapes.

15.2 Studies of Biodiversity in AFS at the Ecosystem and at the Landscape Level

AFS are becoming increasingly relevant worldwide as society has come to recognize their multiple roles and services: biodiversity conservation, carbon sequestration, adaptation and mitigation of climate change, restoration of degraded ecosystems, and tools for rural development (Montagnini 2017a). The potential AFS contributions to the recovery of ecosystem and landscape attributes, such as the restoration and conservation of biodiversity, watershed hydrological services, and connectivity of fragmented landscapes, have recently received special attention (Nair and Garrity 2012; Montagnini et al. 2011, 2015; Montagnini 2017a, b; Calle et al. 2013).

Studies of the impacts of AFS on biodiversity at the landscape level are abundant in the scientific literature. Most research monitoring the contribution of AFS to conservation of biodiversity compare indicators species' abundance and richness among AFS and other land uses prevalent in the region of study (Bhagwat et al. 2008; Redondo Brenes and Montagnini 2010; Teodoro et al. 2011). In addition, several studies focus on the influence of agricultural practices on biodiversity, comparing plots with different management intensities of AFS (e.g., for coffee, Mas and Dietsch 2003; Rossi et al. 2011).

Several landscape-oriented studies have assessed differences in biodiversity among different types of managed and natural ecosystems across the landscape (Tscharntke et al. 2008; Redondo Brenes and Montagnini 2010; Teodoro et al. 2011). For example, Redondo Brenes and Montagnini (2010) assessed the effectiveness of different land-use systems to restore and conserve biodiversity in the Path of the Tapir Biological Corridor in Costa Rica, using birds as indicators. They found that forest fallows, forest edges, home gardens, and silvopastoral systems were the land uses with greater numbers of species of birds. AFS such as home gardens and silvopastoral systems not only housed large numbers of species but also harbored some important endangered species of birds.

In another comparison of biodiversity among different land uses in a tropical landscape, Teodoro et al. (2011) investigated species richness, abundance, and community similarity of arthropods on yellow passion fruit plants, planted in

30 sites along a land-use intensity gradient in coastal Ecuador. The gradient comprised all major land-use types of the area: forest fragments, abandoned coffee agroforests, coffee agroforests managed under shade trees, pastures, and rice fields. Arthropod species richness increased with light intensity and leaf surface area and decreased with land-use intensity: forest fragments and abandoned coffee agroforests harbored significantly more species than rice fields or pastures. Overall diversity in managed coffee agroforests was intermediate between the intensively managed and the more natural habitats such as forests. This trend can be used as a guide when designing and managing AFS with biodiversity objectives: the more intensively managed AFS will have much less biodiversity, while less intensive management will lead to systems which are more similar to natural forests of the region.

15.3 The Most Diverse: Multistrata AFS

15.3.1 Home Gardens

Among the several types of agroforestry used by traditional and more modern societies worldwide, home gardens are sustainable land-use systems that promote preservation of biodiversity and contribute to food security in rural areas. Home gardens are defined as intimate, multistory combinations of various trees and crops, sometimes in association with domestic animals, around homesteads (Nair and Kumar 2006). Traditional agroecosystems, which include “forest gardens” or “home gardens,” combine trees with an understory of annual and perennial crops and sometimes livestock. Villagers live within or adjacent to their gardens and maintain them over many generations. For example, in present-day Mayan towns in the Yucatán Peninsula of Mexico, this type of forest gardens covers about 10% of the region’s area (Noble and Dirzo 1997).

Small, scattered agroforests can provide local or regional environmental services such as conservation of biodiversity (Guindon 1996; Harvey and Haber 1999). Species diversity is common to all home gardens, with food plants (crops and trees) being the most abundant species in most home gardens throughout the world, underscoring the fact that food and nutritional security is their primary role. Next in importance to food crops are cash crops (Nair and Kumar 2006). Species complexity in home gardens is not a natural phenomenon but a result of deliberate attempts and meticulous selection and management by farmers to provide the products they consider important for their subsistence and livelihood; therefore species complexity in home gardens is a man-made feature, unlike in natural systems (Kumar and Nair 2006).

15.3.1.1 Factors Influencing Structure, Composition, and Biodiversity

Numerous studies report on factors influencing biodiversity in home gardens throughout the world, such as remoteness from urban centers, management, and modernization, for example, in Kerala, India (Peyre et al. 2006); in southern Ethiopia

(Abete et al. 2006); in the Peruvian Amazon (Wezel and Ohl 2006); and in Mesoamerica (Montagnini 2006). The practice of home gardens can contribute to conservation needs in regions where deforestation and population growth are constant threats, as is the case in much of the Mesoamerican region (Montagnini 2006). As in other regions of the neotropics, such as Amazonia, present-day home gardens of Mesoamerica represent the reorganization of original indigenous practices as a result of the changes brought by colonization, among which the most outstanding feature was the incorporation of non-native fruit trees and crops. Today, home gardens are of vital importance to the local subsistence economy and food security in the region (Montagnini 2006). Home gardens in Mesoamerica are quite diverse in their vertical and horizontal structure and in their plant species composition. Exotic and native plants are used, with an emphasis on fruit trees. Increasing evidence emphasizes the role of Mesoamerican home gardens as sites for domestication and preservation of useful species. Results of several studies indicate that home gardens of Mesoamerica are rich in biodiversity and need to be considered for in situ conservation and development programs (Montagnini 2006).

In home gardens, plants are generally categorized into three main groups: cultivated, protected, or spared. Cultivated plants are those that are sown or planted by the owner. Protected plants are those that are encouraged by the farmer, whether they are transplanted from zones outside the garden or grow spontaneously in the garden. The farmer may choose to protect or encourage plants, for example, by supporting them or attaching them to a solid structure or by putting stones around them. Spared plants are those that spontaneously grow in the garden and are not removed (Blanckaert et al. 2004). Each of these design and management strategies can contribute to the presence and preservation of species of interest to the farmer and to landscape biodiversity.

Examples of such home gardens span a wide range of climatic and geographic conditions. In home gardens of the Tehuacán-Cuicatlán Valley in Puebla, Mexico, Blanckaert et al. (2004) found high diversity in plant species and uses at 1217 m above sea level with a climate classified as semiarid to arid (total annual precipitation 395 mm). Theoretically, these conditions would place the region at the low end of the spectrum of potential plant species diversity. The most represented plant families were Cactaceae, Araceae, Liliaceae, Solanaceae, and Crassulaceae, reflecting the climatic characteristics as well as the preferences of the local farmers. The plants belonging to both Cactaceae and Solanaceae families in the home gardens are important edible plants: chili (*Capsicum* spp.) and tomato (*Lycopersicum esculentum*) form important ingredients of the Mexican diet.

Home gardens can be most important in regions of dry tropical forest because socioeconomic conditions are more difficult than in other regions, making people rely more on home gardens for self-sustenance. In a semiarid region in eastern Cuba, Wezel and Bender (2003) also reported the importance of home gardens and their high species diversity, with about 50% of the species consisting of fruit trees. Likewise, in the Mexican Plateau, multispecies home gardens cultivated by women and children are useful sites that bring additional biodiversity to desertified areas due to degradation of soils and reduction of biodiversity (Terrones Rincón et al. 2011). These authors propose growing local home gardens that allow the restoration of degraded communities through the plantation of semiarid multipurpose trees which promote soil fertility, reduce climatological impacts, and allow for production of vegetables and medicinal or aromatic plants that are essential in Mexican homes. This emphasizes the importance of home gardens to conserve traditional knowledge, promote environmental education, and promote biodiversity in Mexican ecosystems. In the Otomi-Tepehua region of Hidalgo, Mexico, areas dedicated to home gardens were from 100 to 400 m^2 depending on land tenure in each locality (Araújo Santana et al. 2015). These authors reported a total of 93 species, 82 genera, and 47 families of medicinal, edible, ornamental, and timber uses, with a predominance of medicinal plants. Home gardens have the ability to contribute to family food security, income generation, and permanency of the culture of the region.

Locally, plant diversity of home gardens can also be influenced by the size of the home gardens. For example, in Nicoya, Costa Rica, Lok et al. (1998) found that the size of home gardens ranged from 0.1 to 1.4 ha with an average of 0.5 ha. The smallest home gardens had the highest diversity, with 205–745 species and an average of 348 species per ha. In contrast, the larger home gardens had only an average of 96 species per ha, with less variability among home gardens in comparison with the smaller home gardens.

15.3.1.2 Importance for Species Domestication and Conservation

The high plant species diversity of home gardens makes them an important resource for cultural empowerment and ethnobotanical research. Several current ethnobotanical studies focus on rescuing lesser known fruit and crop species from home gardens of smallholders in Africa, Asia, and other regions of developing countries (Montagnini and Metzel 2017). This type of projects integrates traditional knowledge with scientific research on nutritional values and marketing possibilities, enabling their reproduction in nurseries and commercialization along value chains.

The process of domestication of useful species has long taken place in home gardens in several regions where they are intensely managed and crops are carefully selected for specific purposes. For example, the home gardens of Japanese emigrants in the Tomé-Açu settlement in Pará, in the eastern Amazon region of Brazil, have served as “banks” of potential crop species that have been gathered and closely observed by family members. The home gardens of Tomé-Açu have functioned as validation facilities for farmers making decisions about planting new crops in their farms. Farmers also used home gardens for improvement and propagation of nursery stock (Callo-Concha and Denich 2011).

Several studies emphasize the role of home gardens as sites for domestication and preservation of useful species (House and Ochoa 1998; González-Soberanis and Casas 2004). In El Camalote, Copán, Honduras, House and Ochoa (1998) found several introduced species along with native species that belonged to natural forests of the region, and they stressed the importance of the home gardens as gene banks of ancient crops and as a research field for developing new varieties and cultivars. The diversity of traditional vegetables in the home gardens was outstanding, with many species that are also present in Guatemala and Mexico but that are absent in other parts of Honduras. They cite examples of several edible vegetable species and fruits that today are almost exclusively found in home gardens. Such is the case of the chaya (*Cnidoscolus chayamansa*), a popular green vegetable in Camalote (similar to spinach) but almost absent in the rest of Honduras. They cite other species of vegetables and fruits which, again, are found only in the home gardens of Honduras and Guatemala.

Other examples of domestication of crop species can be found in the Tehuacán-Cuicatlán Valley in central Mexico, where the Maya cultures have a history of over 10,000 years (González-Soberanis and Casas 2004). These authors studied the management and domestication of a fruit of the Sapotaceae family, the tempesquistle (*Sideroxylon palmeri*). This fruit is consumed and commercialized in large quantities in villages of the studied area. Apparently, management of this species in home gardens has resulted in larger, better-quality fruits than those of the wild populations, demonstrating the importance of domestication of plant species by the owners and managers of home gardens. This is a good example of a process of selection by local farmers that may be true for many other species in other home garden settings. Several development projects working with smallholder farmers explore the possibility of finding lesser known species of fruits and medicinal and other species that farmers grow in their home gardens, conduct research to ascertain their nutritional/other values, and help farmers establishing nurseries and reaching markets for their products (Fig. 15.1).

Home gardens may have other positive effects on biodiversity, as they can serve as local refuges for plants and animals that otherwise may be threatened by human or natural disturbances. For example, Griffith (2000) reported that during the 1998 fires in Petén, Guatemala, home gardens and other AFS may have served as critical refuge during a habitat bottleneck for many forest species. Research also indicates agroforestry farms attract birds by virtue of their complex structure—similar to that of intact forest patches—as they harbor insects, provide nesting sites, and offer protection from predators (Griffith 2000). Birds were also attracted by the cultivated fruit trees, which may have provided some of the only food sources in the region after fire destroyed most of the surrounding vegetation. In addition to the many human benefits provided by home gardens, they can supply a multitude of services such as buffers for protecting local biodiversity in times of stress and increased connectivity in biological corridors (Redondo Brenes and Montagnini 2010).

15.3.2 Indigenous and Successional AFS

Several indigenous multistrata AFS which are closely integrated within the forest landscape show remarkable biodiversity (Redford and Padoch 1992). For example, Peters (2018) describes the practices of the Kenyah Dayak people of Indonesia, who manage subsistence orchards and are perhaps the world's most gifted foresters; the Dayak gardens look wild but are carefully cultivated. Bertsch (2017) reviews several well-documented indigenous successional AFS that have been practiced by

Fig. 15.1 In Cameroon and other locations in Africa, the "Tree Crops Development in Africa and Asia to Benefit the Poor" project studies lesser known species of fruits and other species which are part of farmers' home gardens, examines nutritional quality and other characteristics, and helps farmers in the production of seedlings to sell in local markets (Montagnini and Metzel 2017). Home garden in Bangangte, Cameroon (Photo: F. Montagnini)

smallholder farmers over centuries throughout the tropics, identifying similarities in practice, diversity of uses, and economic viability and emphasizing their importance in bridging ecology and agriculture through traditional knowledge. Successional AFS (SAF) are defined as a type of agroforestry which attempts to replicate the spatial and temporal dynamics of forest succession, with plant species assemblages which are planted, maintained, and modified with time to mirror the successional stages of secondary forest development. In the field of restoration ecology, successional processes are often manipulated to meet goals to restore devastated landscapes (Hobbs et al. 2007).

By incorporating succession into agroforestry, farmers can play a key role in ecological restoration through their agricultural pursuits. Such systems have actually been in place for centuries, practiced by indigenous groups under various names. For example, the Lacandon Maya of Chiapas, Mexico, manage succession through a series of distinctly named phases: *milpa* (Spanish for maize field), *arbusto* (Spanish for shrub), and *acahual* (shrub) phase, before being left to return to *selva alta* (high forest) (Diemont et al. 2006). The Lacandon are highly selective of the species planted, deliberately managing species composition for accelerated regeneration of soil fertility (Diemont et al. 2006), and maintaining a high diversity of species offering consistent harvestable crops. In most indigenous SAF systems, trees are not only planted but also encouraged through the selection of naturally regenerating seedlings.

In addition, the practice of attracting wild game is an important component in many types of indigenous SAF systems (Bertsch 2017). Garden hunting is an important consideration in creating diverse habitat, especially in Latin America. Plant species are selected not only to provide for personal consumption and soil fertility but also to attract wild game toward the gardens. Attracting wildlife serves several purposes:

1. Attracts wild game that can be hunted within the garden and provides food and habitat to ensure future generations of desired game species.
2. Visiting animals deposit waste products that further improve soil fertility.
3. By carrying fruit and dropping waste, visiting animals bring new seed sources from outside the agroforestry site.

The Lacandon have also been known to integrate beehives into their fallow systems to supply themselves with honey and to encourage pollination of fruit species growing in the fallow (Diemont et al. 2011). As seen, indigenous SAF systems can contribute to restore and conserve vegetation as well as many elements of the local fauna.

Lessons from the traditional, indigenous knowledge have been adapted to modern agroecosystems mimicking natural forests and successional patterns (Schulz 2011; Young 2017). An examination of SAF practices in NE Brazil showed that this cultivation system actively accelerated natural succession by planting locally adapted edible plants with similar functional characteristics as plants of the same successional level of the local ecosystem. In the first successional step, the main goal is the augmentation of organic material, enabling the integration of plants of a higher successional level in the next step. With increasing development of the successional system, a higher diversity of plants with different functional and structural characteristics leads to shorter nutrient and water cycles. With this method, highly degraded areas have been regenerated, leading to an approximately fourfold increase of agricultural production compared to the annual cropping systems formerly practiced and at the same time reducing the risk of drought-related harvest loss due to crop diversification and use of perennial plants (Schulz 2011).

Likewise, a study of current SAF systems in Nicaragua and Belize has revealed their potential to promote agro-biodiversity, regenerate severely disturbed agricultural landscapes, diversify harvest yields, and reduce ecological and economic risks associated with conventional agricultural systems (Young 2017). Thus the SAF systems are a good example of integration of traditional, indigenous knowledge with current scientific knowledge for the multiple purposes of restoring degraded land, recovering and conserving biodiversity, improving food security, and maintaining local livelihoods in human-dominated landscapes.

15.4 The Quest for "Biodiversity-Friendly" AFS

In many intensively managed production systems, biodiversity conservation is often represented as an economic trade-off between reduced yields and income and opportunity costs. This is often the case in commercial plantations of perennial crops under shade, especially when practiced at large scale. In contrast, in smallholder farms, rich biodiversity and increased yields can coexist, in great part due to greater availability of labor and reduced use of agrochemicals. However, livelihood impacts which sometimes are below expectation if productivity is relatively low are sometimes held up as a major obstacle for wildlife-friendly farming in the tropics (Clough et al. 2011). Compensating the farmers for the extra labor required to produce organic, biodiversity-friendly products can be a means to breach the gap between financial and biodiversity benefits. Several commodities grown as perennial crops in AFS such as coffee, cacao, yerba mate, guayusa, and açaí are examples where price surpluses can serve as an incentive for the farmer to turn to organic/biodiversity-friendly products (Montagnini and Metzel 2017; Rocha et al. 2017).

Arguing that AFS are important for biodiversity conservation, certification schemes are seeking to differentiate commodities on the basis of the biodiversity included in the cropping system, in order to financially encourage more "wildlife-friendly" production systems through market mechanisms. Increasing agricultural intensification may sometimes be the best financial option for farmers, as has been reported for cacao AFS in southern Cameroon (Gockowski et al. 2010). However, true economic opportunities exist for AFS where the buyer is aware and willing to pay a premium for the social or environmental benefits of the product (Montagnini and Metzel 2017; Rocha et al. 2017).

Farmers face challenges when new economic opportunities arise with market growth associated with the perceived greater quality of the organic products. These challenges include environmental concerns arising from land uses designed to supply the increased demand for the preferred products, market competition stemming from expanding cultivation, and access to markets that value the higher quality of traditional small-scale production (Pepper and de Freitas Navegantes Alves 2017).

Marketing of the açaí (*Euterpe oleracea*) which is harvested from forests as well as from backyard gardens in the estuary of the Amazon River in Pará, Brazil, offers good lessons on these issues. Demand for açaí supports the livelihoods of small-scale producers, who could benefit greatly from linking to export markets that value traditional production, which obtains high quality while using more ecologically sound management practices (Pepper and de Freitas Navegantes Alves 2017). Tapping into such markets can certainly provide a boost to the prices family farmers currently get, as their products compete with large volumes of açaí fruit from conventional plantations. Local producer associations and cooperatives that facilitate the collective sale of açaí offer the potential for alternative points of sale with greater possibility of recognizing a higher quality product.

There are several examples worldwide where certification guaranteeing higher quality as well as ecologically sound management facilitates sale of AFS products to specialty export markets (Montagnini and Metzel 2017; Rocha et al. 2017). In combination with the direct sale made possible by aggregating the harvest through producer cooperatives, certification holds the potential to help sustain the livelihoods of family farmers as they confront the evolving market.

15.5 Perennial Crops Under Shade in Agroforestry Systems

15.5.1 Coffee

Coffee-growing ecosystems have significant environmental benefits and social importance. Coffee (*Coffea arabica*) is of paramount economic importance in more than 50 countries worldwide, and the potential exists to influence biodiversity conservation over large areas, although its cultivation can also be a cause of deforestation (Somarriba et al. 2004). In many areas where coffee is grown, as in El Salvador, the landscape has been so severely degraded that the only remaining tree cover is that in coffee plantations (*F. Montagnini*, personal observations 2002).

Many regions of coffee cultivation fall within areas identified as mega-diversity sites (Somarriba et al. 2004). In spite of the relatively small proportion of land in coffee production worldwide, it has a relative impact on biodiversity that does not reflect its scale (Chait 2015). In several countries, coffee production areas overlap with priority areas for conservation that harbor high numbers of species, including endemics; therefore activities that promote biodiversity conservation in coffee AFS can also have impact at both national and regional scales (Somarriba et al. 2004).

Some types of traditional coffee-growing systems, such as shaded agroforests, can maintain landscape biodiversity and decrease market risks by diversifying production. Davidson (2005) reviewed the literature on ecosystem services, especially for biodiversity, on Mexican coffee cultivation, where coffee is grown in five main systems on a gradient following the extent of shade that is incorporated in cultivation systems and how well they represent traditional coffee farms: traditional "rustic" or "mountain" coffee gardens, traditional polycultures, commercial polycultures, shaded monoculture coffee systems, and unshaded monocultures. Agroforestry coffee or "biodiversity-friendly" coffee also provides important social benefits (Gobbi 2000).

The traditional, indigenous coffee AFS harbor relatively high biological diversity and provide high structural complexity (Moguel and Toledo 1999). Traditional coffee systems can also serve as a refuge for wildlife from surrounding areas that have undergone deforestation. Traditional shade coffee plantations illustrate some of the important characteristics of AFS in that they provide habitats for a variety of species, serve as perches and nesting sites, provide food resources, and improve local microclimates that are amenable for a wide variety of birds, mammals, arthropods, and plants (Davidson 2005). Coffee AFS also can serve as sites for seed deposition and germination and act as buffer zones and as biological corridors (Moguel and Toledo 1999).

Mas and Dietsch (2003) surveyed fruit-feeding butterfly species richness and vegetation structure on different shade coffee management systems in Chiapas, Mexico, that ranged from intensive commercial to traditional, rustic systems. Butterfly species richness declined as management intensity increased, with a significant drop between the rustic system and the other more intensive systems, corroborating the importance of preserving rustic, shade coffee production for the conservation of biodiversity. Fruit-feeding butterflies were found to be very sensitive to the intensification of management of the shade canopy, so the authors suggest these butterflies may be an effective way to monitor ecological changes that accompany intensification within the coffee agroecosystem (Mas and Dietsch 2003).

Coffee AFS illustrate well how AFS can reach a compromise between productivity and the provision of environmental services such as biodiversity. Rossi et al. (2011) examined diversity of plants in the understory of coffee AFS and coffee monocultures in Costa Rica, where coffee was managed in a range of systems from medium-organic to high inputs of chemical fertilizers. Diversity of plants declined as management intensity increased, and, conversely, coffee productivity improved as management intensity increased. However, intermediate management intensity produced competitive coffee yields, and organically managed plots had high herbaceous diversity and were as productive as chemically managed plots. The results suggested that it is feasible to manage these AFS for agricultural productivity while maintaining uniform soil cover and a significant number of herbaceous species (Rossi et al. 2011).

Great emphasis has been placed on the number of species of birds affected by coffee production. Shaded coffee plantations in the neotropics play key roles as habitat for migrating birds and therefore have important effects on conservation of biodiversity at supraregional levels (Somarriba et al. 2004). Forest canopies that remain intact through the traditional practices of coffee production under shade house a great number of species of birds. In contrast, coffee farms without shade harbor about half the bird species diversity (Chait 2015). For example, in the 3 most important coffee-growing regions of Colombia, 62 to 106 bird species use shade coffee farms as habitat, with higher numbers than secondary forests in the same region (Sánchez-Clavijo et al. 2008). Apart from the birds, many other species of animals are negatively affected by the increasing amounts of agrochemicals used in conventionally grown coffee monocultures.

It has been shown that the diversity of arthropods and mammals in shaded coffee is similar and sometimes greater than in undisturbed forests (Mas and Dietsch 2003; Teodoro et al. 2011; Rossi et al. 2011; Chait 2015). In addition, diversity of pollinators such as bees correlates with increases in yield, weight of the bean, and quality of the coffee (Chait 2015). To a lesser extent, the diversity of amphibians and reptiles is greater in shaded coffee than in coffee monocultures, likely due to the sensitivity of these groups of animals to pesticides and herbicides. This diversity is significantly altered when the shaded coffee farms are transformed into coffee monocultures (Perfecto et al. 2003, 2007).

15.5.2 Cacao

Cacao (*Theobroma cacao*) AFS can be a viable diversified land use that can improve small farmers' livelihoods and conserve natural resources, as it contributes to the self-sufficiency of families and their farms through a varied production of food and cash crops, and reduced financial and commercialization risk (Cerda et al. 2014; Gross et al. 2016). Cacao plants (either wild or cultivated) growing under shade are another example of how AFS can harmonize productivity, quality, and provision of environmental services such as biodiversity. For example, cacao is cultivated in the states of Bahia and Espírito Santo in eastern Brazil under the so-called cabruca system, where the understory of native Atlantic Forest is cleared and the canopy is thinned out to provide adequate shading for the cacao trees. Apart from its economic and social role, the cabruca system is said to be important for the conservation of Atlantic Forest biodiversity (Rolim and Chiarello 2004).

As for coffee and other crops, for cacao the benefits to biodiversity greatly depend on design and management of the AFS. Findings from cacao agroforestry research in southern Cameroon showed that overall, plant diversity decreased slightly with management intensification, while increased use of fungicides, improved markets, and expansion of the cultivated area were expected to reduce rural poverty (Gockowski et al. 2010). In contrast, in Indonesia, the transformation of the conventional cacao cultivation systems to cacao AFS has improved livelihoods for small farmers whose crops previously yielded poorly due to pests and diseases, with the increased diversity of the cacao AFS contributing to reduce their incidence and impacts on yields (Roshetko et al. 2016).

There are several examples of a good compromise between productivity and biodiversity associated with cacao AFS. Clough et al. (2011) integrated biodiversity and crop productivity data for smallholder cacao in Indonesia to examine the relationship between yield and biodiversity. Species richness of trees, fungi, invertebrates, and vertebrates did not decrease with yield. The authors concluded that moderate shade, adequate labor, and input level can be combined with a complex habitat structure to provide high biodiversity as well as high yields. Their suggestions for increasing biodiversity through management involve increasing the amount of labor per unit area. Specific recommendations include (1) maintaining certain types of shade trees, with moderate shade cover; (2) keeping leaf litter on the forest floor; and (3) reducing pesticide use or replacing pesticides with biological and cultural controls.

Changing farmers' perceptions of the value of shade trees in cacao AFS may be a challenge. To achieve this goal, the authors indicate that it is important to communicate the values that shade trees provide, rather than just encourage farmers to plant trees. However, high biodiversity on cacao agroforests should not serve as a substitute for primary forest conservation, as biodiversity levels were still lower in cacao AFS than in forests (Clough et al. 2011).

Biodiverse cacao AFS are often part of restoration and rural development projects in Latin America and beyond (Cerda et al. 2014; Gross et al. 2016). This is especially true when the biodiversity-friendly product can obtain higher market prices, as for wild and cultivated cacao in the Amazon region of Bolivia (Rocha et al. 2017). In El Salvador, the Cacao Alliance seeks to position the country as an exclusive origin for high-quality fine aromatic cacao in the profitable specialty of gourmet segments on the international markets (Montagnini and Metzel 2017). The Cacao Alliance works with over 6500 producers in 10 departments with a total of 6500 ha of cacao in AFS. AFS with cacao allow for association between fruit trees and other crops, generating social and environmental benefits such as (a) restoring productive landscapes through increased vegetative cover; (b) increasing water infiltration capacity in critical areas for aquifer recharge; (c) implementing technologies and practices of soil and water conservation management; (d) increasing areas with restored biological significance and quality (reduction of ecological niches due to habitat fragmentation); and (e) improving the connections between already established biological corridors to protect native flora and fauna.

These actions, in addition to promoting the restoration of the landscape, also guarantee a reduction in the vulnerability of the productive systems, making them more resilient to climate change. Moreover, the Cacao Alliance promotes agricultural activities that focus on the economic development of more than 6500 families in rural areas, generating greater food sovereignty and employment opportunities in the field (production) and in the city (industry) (Frank Sullyvan Cardoza Ruiz, Environmental Compliance Officer, El Salvador, Cacao Alliance, Catholic Relief Services, personal communication, September 2016).

Intensified but highly diverse cacao AFS have demonstrated remarkably higher yields, net income, cash flow, and family benefits than extensive cacao AFS and are recommended for farming within a land-sparing strategy (Cerda et al. 2014; Gross et al. 2016). Further research is needed to better understand the mechanisms that could regulate synergies or trade-offs to improve this type of intensification.

15.5.3 Yerba mate

Ilex paraguariensis A. St. Hil., Aquifoliaceae ("yerba mate"), is a native tree from South America whose leaves are used to prepare an infusion or tea of popular consumption with a market expanding internationally, as yerba mate is nutritious and energizing and it contains antioxidants (Montagnini et al. 2011; Eibl et al. 2015, 2017). Yerba mate trees are usually grown in monocultures (yerbales) with conventional management resulting in decreased plant productivity and soil erosion in the long term; however, since the tree grows naturally in subtropical forest and is shade tolerant, it is adequate for growing under the canopy of other tree species in AFS.

Yerba mate grows in the Atlantic Forest of southeastern Brazil, northeastern Argentina, and eastern Paraguay, a region which is one of the world's biodiversity hotspots, sheltering about 1–8% of all species worldwide and with high rates of plant, insect, and mammal endemism (Myers et al. 2000; Calmon et al. 2011). The Atlantic Forest is one of the most impacted rainforest areas in the world: once spreading more than 1.5 million km^2, over five centuries of deforestation has resulted in a loss of ~84% (Ribeiro et al. 2009). While only 1% of the original area is protected, deforestation is still ongoing at a rate of 20,000 ha per year (SOS Mata Atlântica and INPE 2014). Agriculture, cattle ranching, and industry have replaced much of the Atlantic Forest, and its diverse fauna is threatened by high-grade logging, hunting, habitat loss, and habitat fragmentation (Cockle et al. 2005; Brewer 2011).

Given the region's large human population, private land ownership, and rapid deforestation, it is important to find economically viable activities that do not result in deforestation. For example, existing parks require buffer zones in which economic activities are limited and, preferably, compatible with conservation. One such activity could be the production of shade-tolerant crops under a tree canopy, such as yerba mate (Brewer 2011).

Incorporating trees in degraded yerbales in the province of Misiones, Argentina, has been shown to provide environmental and economic benefits (Eibl et al. 2017). These authors list 15–20 native tree species that have been tested in different experimental areas and are suitable for growing in association with yerba mate as they have shown good growth, provide good timber, or are valuable for restoration purposes. Species that provide fruit or have medicinal, honey, landscape, or ornamental values are also recommended to increase AFS diversification and landscape biodiversity (Eibl et al. 2015, 2017). As yerba mate AFS can be financially attractive to farmers, emphasis on diversification of its cultivation is increasing, with farmers and institutions devoting time and resources in pursuing the best system for each situation (Montagnini et al. 2011; Eibl et al. 2017).

Argentina is the most important producer of yerba mate (INYM – Instituto Nacional de la Yerba Mate or National Institute for Yerba Mate, www.inym.org.ar). Yerba mate is grown by small or medium to large farmers as a family business, a farmers' cooperative, or large-scale enterprise, both for local consumption and for export. Although due to price instabilities yerba mate production may not be very attractive, organic yerba mate producers can get substantial price surplus on their product; thus interest in organic farming and in yerba mate cultivation under shade is rapidly increasing in recent years (Montagnini et al. 2011; Eibl et al. 2017) (Fig. 15.2). Yerba mate cultivation thus expands a whole range of systems, from extensive monocultures, to AFS with 1–2 tree species for shade, to more complex, multistrata systems in the case of most of the organic yerba mate AFS (Ilany et al. 2010; Montagnini et al. 2011; Eibl et al. 2015, 2017). Therefore it would be interesting to ascertain the role of yerba mate AFS on restoring and conserving biodiversity along a range of cultivating systems which are more prevalent.

With yerba mate being one of the Atlantic Forest region's most widespread crops, it is important to ascertain how these trees can be used by fauna in the region and how plantations may be managed to promote conservation (Cockle et al. 2005). These authors compared bird species' presence and abundance between a forest reserve and an adjacent plantation of shade-grown yerba mate in Paraguay. The study site was located within a 5000 ha tract of Atlantic Forest and an adjacent 80 ha plantation of shade-grown yerba mate which were both similar in terms of elevation, slope, tree species, density of standing dead trees, and abundance of epiphytes. The

Fig. 15.2 In Misiones, Argentina, differential prices paid to organic yerba mate leaves encourage farmers to grow this species in organic AFS, often including native species. Organic yerba mate growing with the native tree *Enterolobium contortisiliquum* (timbo), a valuable nitrogen-fixing tree (Photo: F. Montagnini)

yerba mate AFS was created by removing the forest understory and some trees and planting yerba mate below the tree canopy.

Of the 145 species that were regularly recorded in the forest, 66%, including 5 globally threatened species, were also recorded in the yerba mate AFS. Within the yerba mate AFS, higher tree density did not lead to a greater abundance of forest birds. The authors conclude that yerba mate AFS with native trees could be used to rehabilitate cleared land and allow recolonization by some Atlantic Forest bird species (Cockle et al. 2005). While these results are encouraging, it would be interesting to compare bird abundance and diversity in this type of yerba mate AFS with other modalities for cultivating yerba mate in the region.

As seen, several permanent crops grown under shade are good examples of how agricultural activities can be in harmony with biodiversity conservation. The examples shown here for coffee, cocoa, and yerba mate exemplify cases where domestication of the species has already taken place and the crops are grown in a variety of settings, from multistrata systems practiced by indigenous communities to more simplified systems used in more modern situations and options in between. These all represent a range of opportunities for biodiversity restoration and conservation, with higher positive impacts in the more complex systems. Attention to

Fig. 15.3 Guayusa (*Ilex guayusa*) growing in AFS with native trees in the chakra (farm) of Kichua indigenous people near Tena, in Napo, Ecuador. Photo: F. Montagnini

indigenous practices that might prove more sustainable than more intensive land uses opens up space for a greater role for indigenous peoples in biodiversity conservation, in contrast to "fortress conservation" strategies that would seek to exclude humans from protected areas.

Other permanent crop species like the guayusa (*Ilex guayusa*), where markets have only recently developed at both local and international levels, are still in their early stages of domestication, with research focusing on how to align community needs, markets, and landscape management to improve local livelihoods and biodiversity conservation (Jarrett et al. 2017) (Fig. 15.3). The case of guayusa commercialization has shown that it is possible to integrate indigenous agroforestry with supply chain development while maintaining and even strengthening biodiversity conservation (Logan-Hines et al. 2015; Jarrett et al. 2017).

15.6 Silvopastoral Systems

Cattle grazing has transformed extensive landscapes in tropical America, and this trend is expected to continue as demand for meat and dairy products expands over the next decades (Fajardo et al. 2009; Murgueitio et al. 2009, 2011; Ibrahim et al. 2011). The attention paid to developing sustainable and biodiversity-friendly approaches to livestock rearing typically has not been commensurate with the importance of this land use, perhaps because clearing land for cattle production is considered a most destructive practice for tropical soils, particularly in the humid lowlands. Any recommendations for mitigating the environmental impacts of cattle ranching may be perceived as endorsing a practice that is widely considered ecologically inappropriate (Rice and Greenberg 2004). However research and conservation interest in sustainable pastoral development has been expanding recently, with notorious examples from Latin America and beyond (Murgueitio et al. 2009, 2011; Ibrahim et al. 2011).

A large portion of research on impacts of pasture management on biodiversity has focused on birds, particularly migratory species, because so much is known about their distribution and ecological needs. Furthermore, migratory bird conservation is one area where reliance on preservation of natural habitat alone is not enough to maintain global population numbers (Rice and Greenberg 2004). Birds are one of the groups which are most affected by forest fragmentation produced by the expansion of cattle ranching (Fajardo et al. 2009). The majority of the studies on diversity of migratory birds in cattle ranching areas have been done in the neotropical lowlands. Active pasture with introduced grasses supports very low levels of avian diversity; diversity increases dramatically on pastures where shrub and tree cover is developed (Rice and Greenberg 2004).

Silvopastoral systems (SPS) that involve the combination of trees with pastures and livestock are more complex than grass monocultures and are classified based on the functions and configuration or structure of trees within the system. Examples of SPS are dispersed trees in pastures, live fences in pastures, fodder banks, tree alley pasture systems, and pastures with windbreaks (Pezo and Ibrahim 1999). Because they are more structurally complex than grass monoculture systems, silvopastoral practices also have important benefits for biodiversity. Recent assessments of biodiversity within SPS indicate that many of these systems (e.g., high-density trees in pastures and live multistrata fences) have levels of species richness comparable to those of early secondary forest and that networks of live fences in pastures are important for landscape connectivity (Harvey et al. 2005; Francesconi et al. 2011a, b; Ibrahim et al. 2011). In a study done in Cordoba, Colombia, the structure and composition of bird fauna habitat was evaluated among different land uses between cattle farms, with improved extensive management compared to pastures with low tree density, SPS, old fallows, and secondary forests in advanced stages of succession (Múnera et al. 2009). In this study, the SPS were the habitat that had the greatest total number of bird species, followed by the old fallows, the forest fragments, and the pastures with low tree density (Múnera et al. 2009).

15.6.1 Promoting Biodiversity-Friendly Cattle Ranching

As cattle ranching is expected to continue being an important land use, with possibilities for making it more biodiversity friendly with the use of SPS, efforts are needed to encourage increasing tree cover in pastures, whether the trees are planted or kept and maintained from remnants of former forests (Harvey and Haber 1999). Farmers need to choose a level of tree cover that will provide the expected products and benefits to the system without decreasing pasture productivity. Use of payments for environmental services (PES) mechanisms can be one way to provide incentives for farmers to make their cattle ranching activities more environmentally friendly.

A major project was recently undertaken in Latin America to examine whether payment for environmental services (PES) increased the adoption of SPS on cattle farms (Ibrahim et al. 2011). As part of this research, animal and plant biodiversity in SPS were studied in landscapes dominated by cattle in Esparza (Costa Rica), Matiguás (Nicaragua), and Quindío (Colombia). An environmental service index (ESI) was developed to determine the level of PES. Birds were used as the primary indicator of biodiversity, complemented with studies of butterflies, ants, mollusks, and small mammals. The ESI for biodiversity was based on monitoring of bird species diversity on the main land uses.

The number of bird species observed in pastures with high tree densities or multistrata live fences was higher than that in degraded pastures and grass monoculture pastures and was comparable to the number of species observed in riparian and secondary forest (Sáenz et al. 2007). The percentage of tree cover and the number of tree species were the two most important parameters which explained variation in bird species on different land uses. These data indicate that it is possible to implement SPS that are compatible with both production objectives and biodiversity conservation.

Before the project began, farmers generally managed the pastures with the use of herbicides (3–6 l/ha) to control weeds. The indiscriminate use of herbicides in pastures is associated with high mortality of saplings and juvenile stages of native multipurpose and timber species (Ibrahim and Camargo 2001). With the implementation of PES, the use of herbicides was reduced significantly, which may explain the increase in tree cover in pastures over time.

The inventory of trees in pastures in Esparza and Matiguás showed that there were 8–10 dominant tree species (Murgueitio et al. 2011). In addition to managing natural regeneration to increase tree cover in pastures, private farmers in Costa Rica and Colombia were trained and supported to produce plants of focal tree species (those of interest for conservation). These plants were sold to many cattle farmers receiving PES and were planted along live fence lines and riparian forest that were fenced off to keep cattle away from the riparian forest and water sources.

15.6.2 Enhancing the Use of Native Trees and Palms in Cattle Ranches

The biodiversity benefit of SPS depends on the system components and management, with larger biodiversity in the more complex systems including several tree and shrub species, such as in the SPS of natural regenerating trees in pastures, than in the fodder banks or planted timber trees in pastures. Using native species as part of

SPS confers several advantages to biodiversity conservation (Montagnini and Finney 2011; Murgueitio et al. 2011; Montagnini et al. 2013). An important pool of knowledge has recently developed on native trees and their adaptability to several land-use types including AFS and SPS. For example, more than 130 neotropical species have been screened by various national projects, and several have shown good growth and survival in degraded areas (Calle et al. 2012).

Native trees and palms play important roles in tropical livestock systems. These species provide direct benefits through the production of timber and edible fruits for the cattle and indirect benefits through nitrogen fixation, soil conservation, and natural biological control of pests (Calle et al. 2017). However, relatively few native trees and palms are actively managed by cattle ranchers in the nearly 600 million hectares currently occupied by this activity in Latin America and the Caribbean (Murgueitio et al. 2011).

Cattle ranchers generally control large land areas but have insufficient hand labor and therefore have a limited investment capacity per unit area. This means that they require fast-growing, hardy, or resilient species that will not inhibit pasture growth (Murgueitio et al. 2015). Most species with dense canopies will be rejected by cattle ranchers. Wide-crown trees will be tolerated as long as they allow sufficient light to reach the ground and sustain grass biomass production underneath. Tree management must be simple, especially during the first years, when the direct benefits of trees are still modest (Vieira et al. 2014). All native species that become incorporated into SPS will make an important contribution to biodiversity conservation by providing resources for wildlife (Rivera et al. 2013; Montoya-Molina et al. 2016). Endangered or vulnerable tree and palm species that can be deliberately added to cattle ranching systems will have a lower risk of local extinction.

Calle et al. (2017) proposed adopting the focal species concept in projects that promote SPS in Latin America as a complementary strategy for mainstreaming biodiversity in cattle ranching. In this context, focal species are native trees and palms that can be incorporated directly into SPS, live fences, or riparian buffers to enhance biodiversity and environmental services in cattle-dominated landscapes. For example, a major project called *Mainstreaming Biodiversity into Sustainable Cattle Ranching* (MBSCR) promotes the planting of 50 focal species of native trees and palms of global conservation concern in cattle farms in 5 regions in Colombia (Calle et al. 2015). This set of rare, vulnerable, and endemic species includes trees and palms that grow well in open or semi-open environments, valuable timber trees, and species with important ecological, aesthetic, and cultural value.

The MBSCR project seeks to enhance the connectivity between natural ecosystems in cattle-dominated landscapes through biological corridors and riparian forests. To achieve this goal, the project uses a short-term payment for environmental services (PES) to partially offset investment costs in land uses that are compatible with biodiversity. Livestock farm owners who opt for conservation (preservation of natural ecosystems or ecological restoration) also receive short-term PES. In recognition of the special effort that must be made to adopt focal species, farmers eligible for PES receive an additional bonus for planting and caring for these native species on their farms.

15.6.3 Increasing Complexity and Biodiversity with Intensive Silvopastoral Systems

Intensive silvopastoral systems (ISPS) are agroforestry arrangements that combine high-density cultivation of fodder shrubs (4000–40,000 plants ha^{-1}) with improved tropical grasses and trees or palms at densities of 100–600 individuals ha^{-1}. The ISPS were initially developed in Colombia and have expanded to Mexico and Brazil, among other countries (Murgueitio et al. 2009, 2011; Chará et al. 2017). Several agroecological principles and strategies are applied in both designing and managing ISPS, including (1) use of several layers of vegetation (herbs, shrubs, trees, and palms) to maximize the transformation of solar energy into biomass; (2) reduced dependency on agrochemical inputs and energy, emphasizing interactions and synergisms among biological components to enhance recycling and biological control; and (3) incorporation and promotion of biodiversity into the system components and its surroundings (Chará et al. 2017). Under this situation, biodiversity restoration and conservation are enhanced in ISPS in comparison with SPS and even more so when comparing with conventional treeless pastures.

In ISPS, the canopy cover, tree diversity, and structural complexity of vegetation all contribute to improve habitat for organisms such as birds, mammals, reptiles, and invertebrates that find refuge and food resources (Chará et al. 2015). In cattle ranching areas of Colombia, the ISPS are one of the land uses with the greatest richness of bird species. In El Hatico Natural Reserve in Valle del Cauca, these ISPS have a greater number of species than forest fragments and natural bamboo stands (Fig. 15.4). In other regions of Colombia, the ISPS have been reported to have more species of birds, with about three times as many as pasture systems without trees (Fajardo et al. 2009).

In a study based on interviews with cattle ranchers that adopted ISPS in the La Vieja river watershed, Colombia, 71% of farmers mentioned an increase in the abundance and diversity of birds, 54% reported an increase in general biodiversity of plants and animals on their farms and in the riparian buffer strips, 21% mentioned an improvement in natural biological control, and 11% mentioned an increase in sightings of rare and endangered species (Calle et al. 2009).

In a study at the landscape level in the Andean region of Colombia, the abundance of dung beetles was doubled, and the richness of species was 66% greater in the ISPS as compared to monocultures of grasses without trees (Giraldo et al. 2011). This increase in biological diversity is reflected in the provision of environmental services such as pollination and biological control of noxious organisms for the grasses and the cattle.

At the landscape level, the ISPS can contribute to connectivity among patches of forest as well as to the recovery of strategic sites for the provision of environmental services (Calle et al. 2012). Several examples have been documented where the movement of organisms has been facilitated by SPS. A matrix permeable to bird movement can avoid the collapse of small populations of wildlife that are isolated in forest fragments (Chará et al. 2015).

Fig. 15.4 Intensive silvopastoral system (ISPS) in El Hatico, Valle del Cauca, Colombia. Photo: F. Montagnini

The ISPS are an example of the solution of the false dilemma between land sparing and land sharing as two opposing alternatives for biodiversity conservation. The ISPS are an alternative third way that can go beyond this dilemma based on the natural intensification of the productive systems, with the advantages of the two other options. As it is proposed by the sparing land alternative, the ISPS intensify production in high-yielding systems, and thus they can serve to avoid deforestation. At the same time, ISPS are a form of production that is compatible with the land sharing alternative of designing multi-functional landscapes of high value for biodiversity without sacrificing productivity and economic feasibility (Chará et al. 2015).

15.7 Corridors in the Agricultural Landscape: Living Fences and Windbreaks

15.7.1 Living Fences

The principal role of live fences is to divide, separate, and protect agricultural plots or cattle. They also provide several services and products: fuelwood, fruits, fodder, and shade for cattle, and a major environmental function: they promote biodiversity (Harvey et al. 2005, 2008; Francesconi et al. 2011a, b; Ibrahim et al. 2011). In

Esparza, Costa Rica, Tobar-López et al. (2007) found that species richness of butterflies was higher in multistrata live fences (70 species) than in pastures with high (61 species) and low (45 species) tree densities. In this same area, Rosales and Sáenz (2007) found that mantled howler monkeys (*Alouatta palliata*) preferred riparian forests and forest fragments for daily activities and also used live fences to move within pasture areas.

Living fences promote bird abundance and diversity, providing bird habitat in a similar way forest patches do, and they can also be used by generalist and savanna specialist species. Most importantly for conservation of birds and other fauna, at the landscape level, living fences can provide effective connectivity among patches of forests (Francesconi et al. 2011a, b; Francesconi and Montagnini 2015).

All living fences are not equally effective at attracting birds. As in other AFS, the structure and composition of the fence are important factors influencing their usage by bird species. The presence of birds in living fences could be improved by altering living fence management practices. This could be done by increasing tree diversity, allowing some trees to develop to mature stages, and allowing trees to develop broad crowns (Francesconi et al. 2011a, b). However, some of these features may be not as practical or convenient to the farmer, and as in other efforts to increase biodiversity in AFS, a compromise must be attained between their productive and conservation functions.

15.7.2 Windbreaks

Windbreaks and hedges play important roles, as they are often the only arboreal component of an agricultural landscape, and as such, they provide habitats and resources for animals and for other plants. As living fences do, windbreaks and hedges also function as natural corridors for animal movements across landscapes (Harvey et al. 2005, 2008). Diversity of mammals and birds in hedges and windbreaks depends on their height, structural diversity (number of strata, number of different life forms), species diversity, abundance and diversity of herbaceous plants in the understory, and their management (use of herbicides and insecticides, frequency of pruning, etc.). Thus a set of recommendations on how to use windbreaks to restore and conserve biodiversity includes the following (Harvey et al. 2005, 2008):

- Restore old or degraded windbreaks (fill in gaps, replace old or dead trees).
- Plant new windbreaks to improve landscape connectivity and facilitate animal movements.
- Maintain high connectivity within the network as well as connections with patches of forest.
- Maximize structural and plant species diversity in the windbreaks.
- Include species that provide key resources or habitat for wildlife.
- Include a mixture of perennial and deciduous trees.
- Minimize management of hedges and windbreaks.

Windbreaks tend to be favored by farmers and can be instrumental in biodiversity conservation and landscape connectivity in fragmented areas. For example, forest windbreaks in the perimeter of agricultural fields are frequently used in the Chaco region of Argentina, where about 32% of the original forest remains on average. These windbreaks are about 30–50 m wide and 1700 m long, representing just 5% of the forest area but providing up to 40% connectivity among forest fragments. This means that the windbreaks help to maintain the spatial organization of the landscape and could contribute to the mobility of the individuals of different species among the forest fragments (Tamashiro 2018). Similar to the living fences as well as to other AFS, windbreaks have a variety of agricultural functions, and when focusing on their environmental functions, their design and management must be compatible with their agricultural use.

15.8 Landscape Approach for Agroforestry as Part of Biodiversity Islands

To ascertain the effectiveness of different types of AFS to contribute to conservation as part of biodiversity islands, it is recommended to use a landscape approach, comparing the most prevalent land uses with the natural ecosystems in the region of study. The prevalent land uses in a landscape can be arranged along a continuum of successional stages, from the earliest stages of succession (degraded lands) to more mature stages (forests), with the AFS lying in between these two extremes.

As seen from the information discussed above, the contribution of AFS to biodiversity in managed landscapes varies according to the type of AFS, its management, component species, and position in the landscape matrix. The low-intensive management, multistrata AFS with native species has the greatest potential to harbor the largest biodiversity. As management intensity increases, biodiversity decreases accordingly. However, even the less heterogeneous AFS provides greater biodiversity than would otherwise be realized in conventional monoculture agriculture or in degraded landscapes. In addition, farmers will value and protect AFS as they contribute to their livelihoods, thus ensuring conservation of services they provide, including biodiversity. A number of factors that need to be taken into consideration to design AFS favorable to vegetation and fauna are shown in Tables 15.1 and 15.2.

Biodiversity islands can exist in a wide range of human-dominated landscapes. They may be actively implemented as part of a complex landscape that may include several land uses such as agriculture, forest plantations, and others, or they may be part of a passive management practice, i.e., they may exist as part of the landscapes that were left untouched for practical or economic reasons (Montagnini et al. 2020). The method of implementation is important, as it will determine the characteristics, position in the landscape, and management of the biodiversity island and surrounding landscapes. Landowners can integrate small-scale land sparing to set aside pieces of the property as untouched natural settings to act as biodiversity islands (Montagnini et al. 2020). When coexistence is an end goal, land sharing may

Table 15.1 Main landscape attributes, characteristics of the AFS, and ecological parameters influencing biodiversity in agroforestry systems

Landscape attributes	Characteristics of the AFS	Ecological parameters
Size, shape, and quality of the intact protected forest and fragments of forest	Size, species composition, vertical stratification, horizontal design (rows, circles, hedges)	Habitat requirements (ranges, niches, and food)
Size, shape, and quality of the tree component in the farm (living fences, windbreaks, hedges, riparian forest, etc.)	Shape, configuration, (border/interior relation, length, width, with terracing), and position in the landscape matrix	Sensitivity to fragmentation and to effects on the surrounding environment
Degree of isolation/connectivity of the agroforestry system and the intact forest	Management practices (coppicing, pollarding, pruning, planting, and managing for regeneration)	Mobility and corridor effectiveness (ability to cross open spaces)
Degree of disturbance of the landscape	Minimal use of agrochemicals (pesticides, herbicides) and adoption of biological control measures	Population sizes and rates of population growth (and susceptibility to changes)

Table 15.2 Characteristics of agroforestry that enhance restoration and conservation of biodiversity

How does AFS conserve biodiversity?	Criteria to design AFS for enhancing biodiversity
Providing habitats and niches for other species	Include several tree/shrub species (minimum 8–12 spp.)
Serving as perches, nesting sites	Use preferably native species
Providing food resources	Maintain areas of shade year-round (20–40%)
Improving local microclimate (wind, light intensity, rain, hydrological cycle)	Maintain good canopy height and structure (12–15 m; dependent on species and region)
Serving as sites for seed deposition and germination	Create different plant strata (low-lying herbs, mid-story shrubs, sub-canopy and canopy trees)
Acting as buffer zones between varied land uses in the landscape	Allow growth of epiphytes, lianas, and other plants on shade trees
Acting as biological corridors	Leave dead branches, snags, and stumps
Providing refuge for fauna at times of stress (fire, drought, flood, hurricanes, etc.)	Have live fences, tree hedges, shrubs, and natural secondary vegetation in the farm
Serving as site for genetic differentiation and speciation	Minimize use of agrochemicals, utilize organic and biological control methods
Helping to conserve species that would not live in the wild under current conditions	Minimize tree pruning and other plant manipulations

allow wildlife to thrive in human-dominated landscapes (Crespin and Simonetti 2019). Both land sparing and land sharing can provide valuable protection of species diversity through time (Phalan et al. 2011).

Strategies to restore and conserve biodiversity in human-dominated landscapes may include mitigating threats to biodiversity loss; conserving remaining natural areas as biodiversity islands; protecting, diversifying, and sustainably managing tree cover within the agricultural matrix, including all types of AFS; promoting and conserving indigenous, traditional, and ecologically based agricultural practices; and restoring degraded lands (Harvey et al. 2008). Overall, increasing vegetation cover types in the matrix is an efficient conservation strategy for maintaining higher biodiversity levels in fragmented landscapes. Keeping isolated trees, living fences, and other AFS within the heterogeneous anthropogenic matrix can mitigate land-use intensification (Somarriba et al. 2017). AFS are also important components among land uses in buffer zones of protected areas.

The socioeconomic, legal, and political actions that can promote biodiversity islands in rural environments may include the use of economic instruments, for example, payments for environmental services, and improving environmental laws and enforcement to reduce deforestation, regulate logging, conserve on-farm tree cover, and reduce agrochemical use. Action can also be taken to promote ecologically sustainable production systems such as agroforestry and leveraging local and regional political support for existing initiatives for biodiversity protection.

15.9 Conclusions

With increasing threats to natural ecosystems worldwide due to human population pressure leading to changes in land uses, including deforestation with consequent losses of biodiversity, alternative strategies are needed to restore and conserve ecosystems and landscapes. As landscapes get more fragmented, and reserves and other protected areas lie farther apart, connectivity is needed to ensure pathways to plant propagules and wildlife.

Many examples exist where AFS are a good compromise between biodiversity conservation and the expected outputs of higher productivity and sustainability. Multistrata systems, including home gardens and successional AFS, hold the highest biodiversity, while more simplified AFS designs such as perennial crops and silvopastoral systems with only few trees species for shade fall in the low range for biodiversity. Therefore to favor biodiversity restoration and conservation, AFS need to increase their structural complexity in terms of number of species and strata. However even the more simple AFS design with just one crop and one species of tree/shrub will harbor higher diversity than a crop monoculture or a degraded area. AFS such as living fences and windbreaks can provide connectivity in the fragmented agricultural landscape.

AFS can lie in between land sparing and land sharing strategies. AFS can have a role in land sparing as crops and animals can attain higher productivity than in monocultures, thus resulting in system intensification and decreasing pressure on natural forest areas, grasslands, and wetlands. At the same time, AFS are a good example of land sharing where productivity/sustainability and biodiversity conservation can coexist.

Financial incentives are often needed to promote AFS when increases in productivity brought along by AFS do not fulfill farmer's expectations. Payments for environmental services (PES) have been used successfully in this regard. Use of native species confers greater value for biodiversity than exotics. Knowledge on native species should increase, so they can be incorporated in AFS more frequently. Incentives are needed to encourage farmers to use more native species.

When properly designed and maintained, biodiversity islands can contribute to protect populations of plants and wildlife. AFS can be part of biodiversity islands, especially in buffer zones of protected areas. The more complex AFS can also constitute a biodiversity island themselves. Promotion of AFS should not be used to justify changes in land uses, i.e., cutting forest to establish AFS, based on the fact that AFS can be biodiversity friendly. Rather, AFS should be planned within a broader strategy that contemplates maintaining areas of natural forest in the landscape.

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16 Halophytes for Utilizing and Restoring Coastal Saline Soils of India: Emphasis on Agroforestry Mode

G. Gururaja Rao and Jagdish Chander Dagar

Abstract

Agricultural salinity and sodicity of soils and irrigation waters are an environmental problem in the arid and semi-arid regions of the world. While this problem is natural in its genesis in the coastal regions, it occurs primarily due to anthropogenic activities in the irrigation command areas resulting from over-irrigation in inland areas. It is the product of complex interaction of many variables, which lessen the current and/or potential capability of soil to produce goods and services. In India, reports indicate occurrence of 6.73 Mha of salt-affected soils. Many areas in the coastal belt of 8129-km-long sea coast in India with diverse climatic, physiographic and physical features remain vulnerable to seawater ingress, water logging and salinity problems resulting in the continued crop losses and its economic prosperity. Vast areas are in imminent danger of turning barren, and production and productivity have simply declined due to secondary salinization. Soil salinity problems are further compounded where the groundwater is highly saline, and such areas *by and large* remain barren for want of economically viable technological interventions. The coastal region is likely to face severe challenges in the future due to rise in sea level resulting from global warming. The region, however, is endowed with rich diverse natural resources, and thus, the management of its natural resources, ecological balance and economic prosperity are of paramount importance. Planning for effective and sustainable development of this ecosystem requires adoption of integrated approach to soil and

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water management in the first place and, through it or otherwise, necessary measures to conserve the ecology. To make agriculture viable and sustainable in the coastal environment, the major emphasis should be aimed at (1) soil management, (2) use of poor-quality waters, (3) selection of crops/varieties to suit the environment, (4) suitable agro-techniques including water management and irrigation technologies and water conservation measures through appropriate rainwater harvesting strategies, (5) farming system studies and (6) biosaline agriculture through halophytic interventions. In the present paper, while presenting detailed account of on-farm technologies developed with economic halophytes like *Salvadora persica* and halophytic forage grasses, emphasis has also been made to explore the possibilities of using potential halophytes having importance of food, fodder, fuel, oils, healthcare, ecorestoration, bioremediation applications and their role in restoring the coastal saline soils.

Keywords

Biosaline agriculture · Bioremediation · Coastal soils · Ecorestoration · Halophytes · Salinity

16.1 Introduction

Global demand for food, fibre and bioenergy is growing at rapid rate, and growth in agriculture in most developing countries has failed to catch up with the increase in population growth. Agriculture is the principal lever of economic and social development. The burgeoning human population requires massive amount of food, and to meet this requirement, intensive agricultural practices that are followed have been causing degradation of arable lands due to water logging, salinity, chemical pollution, etc. The situation is more alarming in arid and semi-arid regions of the world with low rainfall and high evapotranspiration. A major factor contributing to human-induced land degradation is soil salinization (Zhu 2001). Salinity-related land degradation is becoming a serious challenge for food and nutritional security in developing countries. As inadequate attention has been paid in the planning stage of irrigation projects, the problems of water logging and salinity have increased at an alarming rate. The increasing problem of salinity of soils and groundwater in the irrigation commands and coastal area is of great concern that needs a holistic approach for its management. Salinity is a perpetual problem in coastal areas where salinity issues are resulted from both natural and anthropogenic forces (Boesch et al. 1994; Rogers and McCarty 2000) resulting in decline in agricultural crop productivity due to degraded landscape (Yeo 1999). Salt stress severely limits the plant growth and yield; in fact, no toxic substance restricts the plant growth more than salt globally (Xiong and Zhu 2002).

Agriculture, horticulture, aquaculture, animal husbandry, etc. are the primary livelihoods of the people living in the coastal areas of India, but the productivity of all these sectors is much below the national average because of various constraints related to soil, water and climate. The socio-economic status of the population living in coastal areas is also much below the national status. It is essential that coordinated strategies for conservation and scientific utilization of the rich diverse natural resources of the coastal region are adopted for improving the productivity and the livelihood of millions of resource-poor farmers and to protect the coastal environment from the potential environmental threats.

For maximizing crop productivity, these areas need to be brought under high-yielding salt-tolerant crops/plants, preferably in agroforestry mode. Due to the narrow threshold limits of salt tolerance of many agricultural crops, the use of economic halophytes has been found as an alternate strategy since these species have capacity to accumulate and/or exclude the salts and also constitute good source of food, forage, oils and medicines apart from the ecorestoration of such lands. Methods for salt removal include breeding for salt tolerance and further their use with ideal agronomic interventions or phytoremediation (biosaline agriculture). The former has limited applicability primarily being a cost- and labour-intensive approach and also due to narrow range of salt tolerance of agricultural crops. On the contrary, phytoremediation by halophytes and salt-tolerant plants forms an ideal approach as it can be managed effectively under field conditions (Hasanuzzaman et al. 2013a, b; Munns 2005; Manchanda and Garg 2008). In this chapter, while presenting detailed account of on-farm technologies developed using halophytes of economic importance, emphasis has been made to explore the possibilities of using potential halophytes having importance of fodder, fuel, oils, healthcare, ecorestoration, bioremediation applications and their role in restoring the coastal saline soils of India, preferably in agroforestry mode.

16.2 Extent of Coastal Saline Soils and Causes of Salinity Development

It is reported that about 6.73 Mha of land is salt-affected in India including the coastal areas (Singh et al. 2010; Fig. 16.1). The problems of environmental degradation are diverse and complex due to their ecological fabric in India. While some of the problems are widespread and operate over long term, others are mainly localized

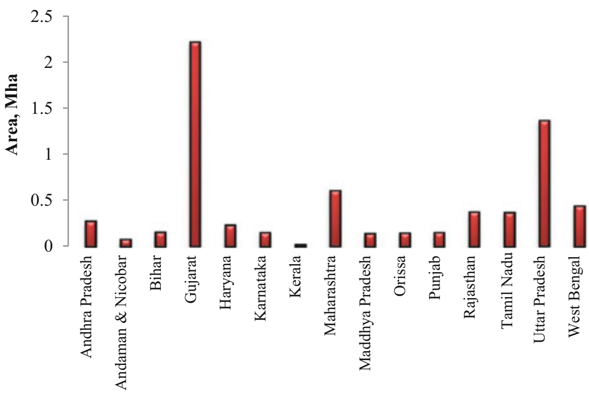

Fig. 16.1 Statewise distribution of salt-affected soils in India (Mha) (total area: 6.73 Mha)

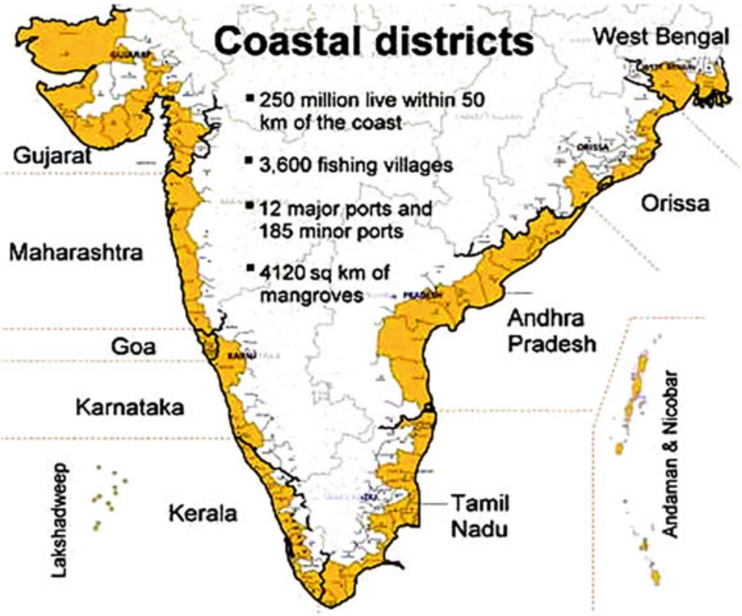

Fig. 16.2 Coastal belt of Indian subcontinent

and more intense in their impacts. Soil and water salinity problems are essentially multisectoral and are complex in nature. Vast areas are in imminent danger of turning barren, and production and productivity have simply declined due to secondary salinization. Soil salinity problems are further compounded where the groundwater is highly saline, and such areas *by and large* remain barren for want of economically feasible technological interventions, thereby affecting the livelihood of the farmers because of low productivity of the existing farming practices.

Coastal ecosystem poses a delicate equilibrium between land and water masses among its different components but with high degree of vulnerability in spite of bountiful natural resources. India has a long coastline of 8129 km spread over as many as nine states, two union territories and two island ecosystems (Fig. 16.2) and has been subjected to many spells of sea-level changes. Natural calamities like cyclones, storms, tsunami, sea ingress and tornado are common. The major salinity-related problems encountered in coastal region include:

- Lands are subjected to the influence of tidal waves and periodical inundation by tidal water.
- Shallow water table enriched with salt contributes to increase in soil salinity during winter and summer month.
- Heavy rainfall results in excess water during Kharif season.
- Poor surface and subsurface drainage conditions.

- Lack of good-quality irrigation water.
- Poor socio-economic conditions of the farming community restricting them to adopt improved and high investment technologies.

16.2.1 Salinity Build-Up in Soil

Salinity build-up in soil due to ingress of saline groundwater takes place through the excessive and heavy abstraction of groundwater from the coastal plain aquifers; seawater ingress; tidal water ingress; relatively less recharge; and poor land and water management. Over-exploitation of good-quality groundwater (which floats on saline groundwater) has rendered it vulnerable to sea intrusion in coastal areas rendering danger to the sensitive aquifers on which a major chunk of the population depends primarily for water. Intrusion of salty water takes several forms such as horizontal intrusion that occurs as the saline water slowly pushes the fresh inland groundwater landward and upward. The cause can be both natural (due to rising sea levels) and anthropogenic (abstraction of freshwater which floats on saline water from the coastal wells). Pumping from coastal wells can also draw saltwater downward from surface sources such as tidal creeks, canals, etc. Options for control of seawater ingress into aquifers include (1) modification of groundwater pumping and extraction patterns; (2) artificial groundwater recharge; (3) injection barriers; and (4) subsurface barriers and tidal regulators, check dams and reservoirs (Sen et al. 2012; Gururaja Rao et al. 2012a, b, 2013, 2014). However, for an effective and long-term solution to the problem of seawater intrusion in the coastal plains, it is vital to develop location-specific optimization methods and models to identify and earmark ideal and suitable locations of the pumping wells and rates of withdrawal of the groundwater. Studies carried out by Central Soil Salinity Research Institute (CSSRI) through artificial recharge of groundwater (Gururaja Rao et al. 2012a, b, 2013, 2014) and the efforts in its use for irrigating crops through drip irrigation in diverse crops including tree plantations have paid dividends.

16.2.2 Irrigation Water Resources

With a vision on source-wise water allocation for irrigation for enhancing the crop productivity and maintaining the stability of the coastal region, studies by Sen et al. (2012) indicated a stepwise increase in water use under different modes along with suggested increase in cropping intensity from 150 to 225% during 2020–2050 (Fig. 16.3). Field water balance model has been used to estimate surface water storage opportunities which gradually dominate over groundwater use for stability of the coastal plain.

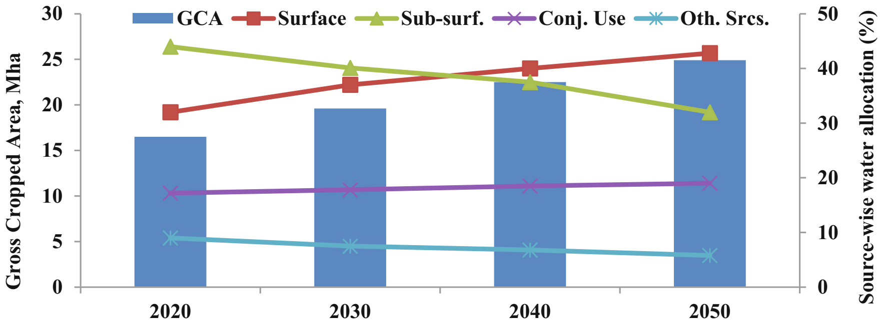

Fig. 16.3 Source-wise water allocations with respect to total amount of irrigation water and the gross cropped area during coming four decades in the coastal areas of India. Source: Sen et al. (2012)

16.3 Halophytes

Halophytes are naturally 'salt-loving' plants that grow optimally in an environment with high salinity and have the ability to complete their life cycle under highly saline (NaCl) conditions (Khan and Qaiser 2006; Stuart et al. 2012; Arora and Dagar 2019) and can survive and reproduce in environments where the salt concentration exceeds 200 mM of NaCl (~20 dS m^{-1}, Flowers and Colmer 2008). Halophytes are usually divided into three groups, namely, obligative (true) halophytes, which invariably need salt for their optimal growth and metabolism (saline soil of above 0.5% NaCl level), e.g. *Suaeda fruticosa*, *Cressa cretica*, *Salsola baryosma*, *Atriplex* spp., etc.; facultative halophytes, which obtain optimal growth on saline soil like true halophytes and can also grow and adapt on non-saline soils, e.g. *Trianthema triquetra*, *Salvadora persica*, *Tamarix dioica*, etc.; and glycophytes or transitional halophytes, which are found growing at transition of saline and non-saline areas and achieve optimal growth at non-saline niches of the salt basins, e.g. *Sporobolus marginatus*, *Haloxylon salicornicum*, *Dactyloctenium sindicum*, etc. (Arora and Dagar 2019). Halophytes have the potential for salt removal to restore saline soils (phytoremediation) and occupy niches from the marine to the arid and from salt deserts to salt marshes; and this range of habitats is reflected in a variety of recognized 'physiotypes' (Gururaja Rao et al. 1993, 1994; Gururaja Rao and Singh 1998). There are diversified species of halophytes suited to grow in different saline regions throughout the world including coastal saline soils, soils of mangrove forests, wet lands, marshy lands, arid and semi-arid regions and salinized agricultural lands (Hasanuzzaman et al. 2014, 2019; Dagar 2018). Halophytic plants provide options for livestock feeding in both arid and saline landscapes. These plants are variable in both biomass production and nutritive value, and they are characterized by slow growth, low digestibility (therefore low metabolizable energy) and high content of antinutritional factors. Many species are the indicators of a particular type of saline or sodic soil (Arora and Dagar 2019), and many of them develop specific adaptation mechanism such as succulence (*Suaeda*, *Arthrocnemum*, *Sesuvium*, etc.); short life cycle (ephemerals like *Cardamine hirsuta*, *Arabidopsis thaliana*); root filtering, e.g. in mangroves; development of salt glands or pumps (*Atriplex*, *Tamarix*, *Cressa*); and many morphological and anatomical adaptations (e.g. in mangroves phenomena like vivipary, pneumatophores, knee roots, thick waxy leaves, etc.). In the light of searching suitable agricultural crops for saline agriculture, Aronson (1989), Dagar (2003) and Dagar and Singh (2007) included those plants which are found growing well in natural saline habitats and thrive well when irrigated with saline water with electrical conductivity (EC_e or EC_{iw}) of 8 or more dS m^{-1} under halophytes. Those which grow well in the tidal zone (mangroves and associates) or can be cultivated successfully with seawater irrigation or water with EC_{iw} 30 dS m^{-1} must be recognized as true halophytes.

Saline agriculture is a prospective area of research where the genetic resources of halophytes and salt-tolerant plants could be utilized for producing human and animal diet and a variety of other raw materials on saline wastelands using saline irrigation waters. Salt-tolerant plants represent only 2% of terrestrial plant species, but they represent a wide diversity of plant forms (Glenn and Brown 1999; Flowers and Colmer 2008). They have the ability to complete their life cycle in NaCl-rich environment where almost 99% of salt-sensitive species die because of NaCl toxicity and thus may be regarded as a source of potential new crops (Glenn et al. 1997). Halophytic species possess a range of highly efficient and complementary morphological, physiological and anatomical characteristics to combat and even benefit from a saline environment (Flowers and Colmer 2008; Shabala and Mackay 2011).

16.3.1 Mechanism of Adaptation of Halophytes Under Saline Condition

Halophytes are equipped with well-defined adaptive mechanisms that enable them not only to withstand periodical high salinity but also to complete their entire life cycles at high salinities (Flowers et al. 2010). The tolerance of halophytes to salinity relies mainly on the controlled uptake of ions and the vacuolar compartmentalization of Na^+, K^+ and Cl^- with the achievement of an osmotic balance between vacuoles and cytoplasm by synthesis of osmotically active metabolites (Sagi et al. 1997; Flowers and Colmer 2008). Majority of the halophytes are deep rooting perennials that achieve their optimum growth and yield potential at thresholds between 6 and 25 dS m^{-1} (ECe), levels at which virtually all of our modern crops would perish. Some of the more prolific ones thrive in the coastal saline soils and arid inland saline soils with concentrations of salts (ECe) as high as 45 dS m^{-1} and above, e.g. *Salvadora persica* (Gururaja Rao 1995, 2012; Gururaja Rao et al. 2004a, b, 2017; Reddy et al. 2008). With their vigorous growth and root development, these plants are often able to take advantage of less saline moisture within the soil profile and adapt to seasonal variability in salinity by altering germination, growth and reproduction cycles to best suit their survival needs (Dagar 1995a, b, 2003; Arora and Dagar 2019). Several halophyte species including grasses, shrubs and trees can remove the salt from different kinds of salt-affected problematic soils through salt excluding or excreting or accumulating by their morphological, anatomical and physiological adaptation in their organelle level and cellular level (Arora et al. 2013; Arora and Gururaja Rao 2017; Arora and Dagar 2019). In general, halophytes produce *by and large* salt-free seeds which require freshwater for proper germination. However, there are exceptions among the extreme ones which are able to germinate even at salinity half the concentration of seawater, e.g. *Salvadora persica* (Gururaja Rao 1995, 2015; Gururaja Rao et al. 1993, 2003, 2004a, b; Gururaja Rao and Singh 1996). For detailed account on adaptations among halophytes (morphological, anatomical, seed morphology, seed germination behaviour, and physiological traits) against high salinity, see Arora and Dagar (2019).

The major hallmark of all halophytes is their ability to use inorganic ions such as Na^+ and Cl^- (available in the external media 'for free', i.e. ions capable of being taken passively along the electrochemical gradient without spending any energy (ATP) to drive this process) for osmotic adjustment in their tissues when grown under saline conditions. Halophytes tolerate these ions because of their superior ability to sequester cytotoxic Na^+ in root and leaf cell vacuoles—a trait conferred by the constitutive expression of tonoplast Na^+/H^+ NHX exchangers (Apse and Blumwald 2007) complemented by the efficient control of slow (SV) and fast (FV) vacuolar ion channels (Bonales-Alatorre et al. 2013) to prevent Na^+ from leaking back into the cytosol. In contrast, glycophytic crops possess only a limited ability to use Na^+ for osmotic adjustment and rely heavily on de novo synthesis of organic osmolytes.

Soil salinity is an abnormal growth condition and thus perceived as a stress in glycophytes, whereas for halophytes, it seems more appropriate to describe salinity as normal and more of a constraint. Halophytes have evolved to manage and adapt to these constraints, employing a number of physiological mechanisms (biochemical and morphological) that enable them to tolerate the elevated concentrations of sodium and chloride in soil. Some of the adaptation mechanisms are briefed below:

Osmoregulation The most distinguishing feature of halophytes to tolerate high salt concentration is known as osmoregulation, i.e. their enhanced ability to regulate osmotic imbalances that result from increased salinity (Flowers et al. 1986). By maintaining high internal salt levels, they not only maintain adequate water uptake and cell turgor necessary for cell growth but also avoid many of the associated ill effects of dehydration, i.e. nutrient deficiencies and specific ion toxicity (Gururaja Rao et al. 2004b). Halophytes depend on a combination of interrelated processes that enable them to manage osmotic imbalances. Osmoregulation is the basic underpinning of salt tolerance in halophytes whereby the cytoplasm continues its normal function in spite of increased salt accumulation.

Salt Exclusion and Excretion Salt exclusion by the plant's roots is often described in terms of elemental substitution or the preferential ion selection of potassium over sodium. Salt compartmentation at organ level and cellular level is another tolerance mechanism (known as intra-plant allocation) that predominates at the root level and contributes to overall plant salt tolerance. Well-defined salt compartmentation mechanism at organ level has been demonstrated in *Salvadora persica* (Gururaja Rao et al. 1999a, b) and forage grass *Dichanthium annulatum* (Gururaja Rao et al. 2001b, 2005). Excretion, another self-regulating behaviour, is often characterized by the secretion of salty sap through epidermal pores, glands and bladders located on the plant's roots, shoots and leaves. Intercellular transport mechanisms (pumps) move excess salt ions from surface cells to the outside of the leaf or stem leaving visible salt deposits once the water is evaporated. The more highly evolved halophytic grasses, shrubs and trees employ this device regularly in order to desalinate internal fluids by excreting sodium and chloride ions at critical periods in their development.

Succulence and Abscission Some halophytes are succulents and have the capacity to sequester sodium ions in vacuoles within the cell by active transport mechanisms and intracellular pumps that help maintain constant levels of salt within the cytoplasm. This inhibits ion toxicity and helps maintain cell turgor while, slight accumulation of water, potassium and organic constituents (i.e. proline, mannitol, sucrose and glycinebetaine) keep the cell sap from dehydrating and allow proper function of essential metabolic processes (Flowers and Colmer 2008). Increased protein production is a direct response to the increased salt content and changing osmotic requirements of the cell (Gururaja Rao 2015). Another efficient desalination mechanism, the abscission or die-off of older salt-rich leaves and stems (and the subsequent regrowth of new salt-free ones), has a similar detoxifying effect, ensuring plant survival through continuous cycles of salt purges. This is clearly evident in halophytes like *Salvadora persica* (Gururaja Rao et al. 2003) and *Suaeda fruticosa*.

16.3.2 Potential Uses of Halophytes

Halophytes have multiple uses, viz. as food, feed, wood and biochemicals and in landscaping, ornamentals, industrial raw materials and bioremediation (Koyro et al. 2011; Dagar 2018). However, their domestication for economic production requires the refinement of growing protocols and selection of improved varieties. Halophytes are remarkable plants, and their use as food for humans and forage/fodder (Fig. 16.4) for livestock may be compromised by the high salt concentration of the vegetative tissues, although systems can be developed using feed mixes for livestock ruminants (Norman et al. 2013).

16.3.2.1 Halophytes as Alternate Food Crops

The agricultural use of saline water or soils is an important approach in the management of saline wastelands. At present, 30 plant species provide 90% of human food with rice, maize, wheat and potato making up 50% of this value (Khan et al. 2006; Khan and Ansari 2008). At the same time, non-conventional crops (including halophytic crops) are seen as an alternative for farming in regions where only saline waters and saline soils are available and freshwater is considered a

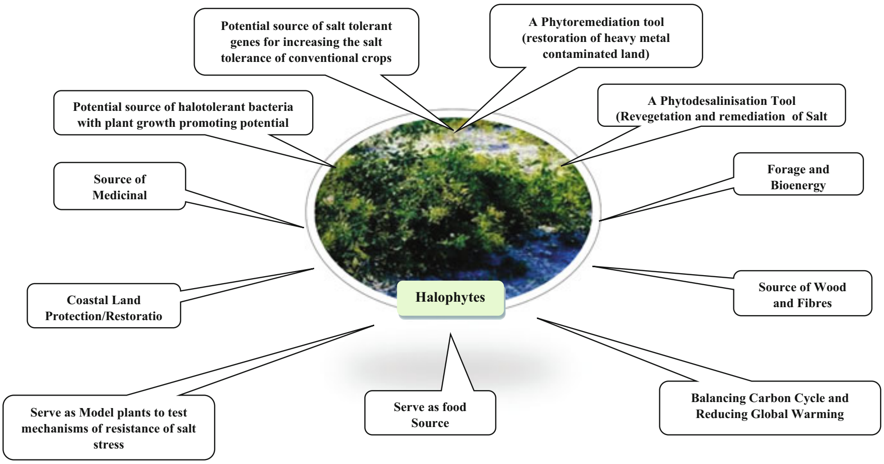

Fig. 16.4 Halophytes and their uses

scarce resource. The use of diverse halophytes as valuable cash crops could be a suitable option in such hostile environments. Identification of economic halophytes and salt-tolerant plants and also the feasibility of using saline water for irrigation would form an important management strategy for bringing coastal soils under production through saline agriculture.

There has been a shift from producing halophytes as animal feed or salty vegetables for human consumption, to the mass production of non-food crops. Halophytes (e.g. *Crithmum maritimum*, *Portulaca oleracea*, *Salicornia* spp. and *Aster tripolium*) have been used for human consumption (Tardio et al. 2006). These species can synthesize secondary metabolites such as osmolytes and scavengers of reactive oxygen species (Hasegawa et al. 2000). The secondary metabolites include simple and complex sugars, amino acids, quaternary ammonium compounds, polyols and antioxidants (e.g. polyphenols, β-carotene, ascorbic acid and ureides) (Ventura and Sagi 2013). Osmolytes can potentially be utilized in functional foods with disease-preventing and/or health-promoting benefits (Buhmann et al. 2010; Buhmann and Papenbrock 2013a, b). Halophytes such as *Salicornia bigelovii* and *Aster tripolium* are good source of vegetables, salads and vegetable salt (Böer 2006). A number of other halophytes, e.g. *Salsola soda* and *Beta maritima*, have great potentials as novel sea vegetables. The year-round availability of *Salicornia* crop makes it a good source of halophytic vegetable (Böer 2006). Seeds of psyllium (*Plantago ovata*) and quinoa (*Chenopodium quinoa*) are widely used as alternative foods, particularly in breakfasts as healthy and medicinal food. Asparagus (*Asparagus officinalis*), cowpea (*Vigna unguiculata*), mustard greens (*Brassica juncea* var. CSR 54 and CSR 56), cluster bean (*Cyamopsis tetragonoloba*) and Amaranthus (*Amaranthus spinosa*, *A. viridis*) are used as vegetables. These along with other food crops such as barley (*Hordeum vulgare*), safflower (*Carthamus tinctorius*), sesamum (*Sesamum indicum*) and pearl millet (*Pennisetum purpurium*) could be cultivated

Fig. 16.5 *Salicornia bigelovii* on highly saline soil

with success along with fruit trees such as *Carissa carandas*, *Emblica officinalis* and *Aegle marmelos* irrigating with saline water of ECiw 10 dS m^{-1} in agroforestry mode (Dagar et al. 2016). Other fruit trees which could be established with saline water included *Ziziphus mauritiana*, *Feronia limonia* and *Cordia rothii*. *Capparis decidua* is another important useful bush of saline areas producing fruits of economic importance used in pickles.

Many halophytes have been tested as vegetable, forage, and oilseed crops in agronomic field trials. The most productive species yield 10–20 Mg ha^{-1} of biomass on seawater irrigation, equivalent to conventional crops. *Salicornia bigelovii*, an oilseed halophyte, for example, yields 2 Mg ha^{-1} of seed containing 28% oil and 31% protein, which is similar to soybean yield and seed quality (Glenn et al. 1997; Glenn and Brown 1999). Many plant species have been used traditionally as herbs and vegetables (Ventura and Sagi 2013).

The glasswort (*Salicornia bigelovii*) is a leafless salt marsh annual plant (Fig. 16.5) with green jointed and succulent stems indigenous to the Arabian Sea coasts of Pakistan and India. It is extremely salt tolerant and being used as salad (greens), while the seed forms a good source of high-quality edible oil; the residual meal provides superior feed for livestock and shrimp/fish. It produces seeds with 30% oil and 35% protein; the oil is similar to safflower oil and hence suitable for edible oil production. In addition, *Salicornia* stem and straw can be utilized as cut hay in mixed feeding regimes, manufactured into pressed board for construction purposes or in paper making.

Commercial cultivars of *Salicornia bigelovii* in Mexico have been demonstrated with seed yields of 2 Mg ha^{-1} with an overall biomass production of 20 Mg ha^{-1}. The high-protein edible oil has a fatty acid composition, similar to that of safflower. When mixed with traditional fodder, the residual meal makes for an excellent feed supplement. A number of other species including *S. rubra*, *S. europaea*, *S. herbacea*, *S. peruviana* and *S. virginica* possess similar commercial potential. Select varieties of *S. brachiata* are now being cultivated in the deserts of India for value-added by-products like vegetable salt (Attia et al. 1997). Due to their easy cultivation, even at seawater salinity, *Salicornia* species have been mainly grown for multipurpose applications that include biodiesel, oil, bioremediation, forage, vegetable and ornamental usages.

Salicornia cultivation which is a new attempt in India was grown on saline soils with seawater application. For utilization of costal saline soils, agrotechnology of *Salicornia brachiata* was perfected, and in the process, germplasm was also improved for higher yield with recurrent selection (CSMCRI). While looking for a solution to minimize the cultivation cost, it was found that densification of the species in its natural habitat where the species naturally grows may minimize the cultivation inputs, since natural inundation of seawater can take care of irrigation.

To make *Salicornia* cultivation economically viable, besides oil and vegetable tips, a process to produce vegetable salt from the waste biomass after removing the seeds for oil was developed. The vegetable salt contains several important nutrients besides sodium chloride not normally found in sea salt. Due to the presence of low sodium, it is considered to be beneficial for patients with heart problems. The technology of vegetable salt preparation was transferred to a local entrepreneur for commercial production.

Salicornia brachiata is cultivated in India (Tamil Nadu, West Bengal) and Sri Lanka primarily for its oil. An improved variety of *Salicornia* (SOS-10) is a hybrid between a salt-resistant and a highly drought-resistant species grown extensively by private companies in India (Gujarat and Rajasthan). *Salicornia* species grow on different soil types: sandy, loamy and clayey ones. The plants tolerate very alkaline and saline soils and submersion by seawater, but they prefer organic, sand and sandy loam soils and regular irrigation with seawater. *Salicornia* resists the highest salt concentrations to a maximum of 50,000 ppm. It can be protected from higher salt concentrations in the soil by flushing the salt below the rooting zone and, if possible, back into the sea.

Studies conducted by Pandya et al. (2006) revealed that application of nitrogen (N) up to 100 kg ha^{-1} had significantly increased the seed yield (29 and 87%) and plant biomass (29 and 51%), over 75 and 0 kg N ha^{-1}, respectively. Plant characteristics like canopy, spike length, number of segments and harvest index were also found increased with the increase in N application. An application of 75 kg P_2O_5 ha^{-1} was also found to be significant with an achievement in higher seed yield production (48%) and number of spike segments (43%) over the control. The interaction study between the applied doses of N $\times$ P was found significant at highest fertilizer levels (N-100 $\times$ P-75 kg ha^{-1}) and produced maximum seed yield over the control but remains at par in case of plant biomass. The plant nitrogen content in biomass (spike + seed) though found increased with N application has remained at par in case of P application (Table 16.1). Nitrogen and potassium content and uptakes were found increased significantly with N application. The plant density had a significant effect on yield, biomass and other important yield attributes. Plant canopy increased significantly during different phases of growth. The findings here indicate potential benefit of *Salicornia brachiata* if resorted and integrated to crop production system in saline soils intruded with seawater for enhancement of scope of sustainable marine ecosystem and as remedial measure

Table 16.1 Effect of phosphorus on yield and yield attributes in *Salicornia brachiata*

	Seed yield	Dry biomass	Plant height	Canopy spread	Main branches	Spikes/ branch	Spike length	Segments	HI
Phosphorus levels	kg ha^{-1}		cm		Number		cm	Number	%
P_0	571.6	5192	30.10	123.9	33.2	424.2	9.80	5.7	24.9
P_1	609.0	6016	31.70	125.9	33.3	423.8	11.00	5.9	28.9
P_2	846.2	7144	30.20	122.3	34.1	564.2	11.40	8.2	41.8
S.Em	88.10	759.2	0.51	4.51	2.91	52.06	0.56	0.49	13.1
LSD ($p \leq 0.05$)	215.6	NS	NS	NS	NS	NS	NS	1.72	NS

P_1 and P_2 indicate phosphorus application at 50 and 75 kg ha^{-1}, respectively; *HI* harvest index
Source: Pandya et al. (2006)

Fig. 16.6 High-density crop of *Salicornia brachiata*

Fig. 16.7 *Kosteletzkya virginica* (Photo: G. Gururaja Rao)

of coastal saline agriculture of world inclusive of salt-affected waste lands. Optimum plant density of 278 plants 10 m^{-2} and 100 kg N ha^{-1} and 75 kg P_2O_5 ha^{-1} improved the vegetable biomass and oil of *Salicornia brachiata* (Fig. 16.6; Table 16.1) which is of immense help to the producers with a new alternative cropping system having high industrial potential for its valued nutritional salt and linoleic rich oil and plant bioactive derivatives.

Rabhi et al. (2009, 2010) reported that *Arthrocnemum indicum*, *Suaeda fruticosa* and *Sesuvium portulacastrum* seedlings grown on a saline soil significantly reduced the soil salinity by absorbing soluble salts mainly sodium ions. They also further reported that *Sesuvium portulacastrum* was able to accumulate nearly 30% of Na^+ content in shoot.

The seashore mallow (*Kosteletzkya virginica*, Fig. 16.7), a perennial, is a salt-tolerant plant that grows wild on the coastal marshlands or inland brackish areas and serves as a source of both feed and fuel. Seeds possess about 18% oil which is similar to soybean oil with fatty acid composition similar to cotton seed oil.

An important feature of halophytes is that they do not generally accumulate salts in their seeds, enhancing their potential for immediate use without any treatment. The relatively small size of their seeds, which is considered disadvantageous in harvesting and processing, can often be compensated for by relatively high yields. Grain Amaranth (*Amaranthus caudatus*, *A. cruentus*, *A. hypochondriacus*), although regarded as staple food, is an example of extremely small grain with superior nutritive qualities. Similarly, a number of salt-tolerant cereal grasses (species of *Distichlis*, *Pennisetum*, *Sporobolus*, *Echinochloa*, etc.) and *Chenopodium* produce large amounts of high-protein rich seeds with a good balance of amino acids and essential fatty acids, essential vitamins and minerals and important starches/ carbohydrates. Quinoa (*Chenopodium quinoa*) has been recognized as a very potential food crop across the globe, and some varieties can also be cultivated using seawater for irrigation. Ismail et al. (2019) have reported that some lines could produce 10 Mg ha^{-1} seed yield using saline water up to EC 14–18 dS m^{-1}. This study is significantly important for the dry ecologies. The use of saline and brackish water resources has been recommended for growing cash crops as food, fuel, fibre, fodder and medicine (Dagar 1995a, b, 2003, 2005, 2018; Rozema and Flowers 2008; Dagar et al. 2006; Rozema and Schat 2013) for the ever-burgeoning population.

16.3.2.2 Halophytes as Source of Fodder and Forages

Halophytic grasses, shrubs and trees containing digestible protein levels comparable to conventional livestock feed used to be grown as fodder. Forage and fodder species account for the bulk of commercial halophyte cultivation, viz. grasses, such as species of *Distichlis*, *Brachiaria*, *Chloris*, *Dichanthium*, *Paspalum*, *Spartina*, *Panicum*, *Sporobolus*, *Aeluropus* and *Eragrostis*; shrubs, including species of *Atriplex*, *Salsola*, *Kochia* and *Suaeda*; and trees such as species of *Salvadora*, *Acacia*, *Pongamia*, *Tamarix* and many others. The halophyte diet appears to have contained balanced nutrients which render their high salt level less detrimental than adding the same salt levels to Bermuda grass hay (Swingler et al. 1996). Earlier reports indicated halophytic grass when fed, the cattle gained weight equally to maize fodder fed ones (Khan and Ansari 2008). Thus, combination of halophytes with conventional hay or maize is a viable alternative. Because of the ease of cultivation on saline farmlands of halophytic grasses, many farmers could maintain the productivity of such farms. Due to the relatively high salt content in their tissue (between 10 and 50% of their dry weight), the potential is greatest when interplanted with native forage or used in mixed feeding regimes as a dry season browse and fodder supplement.

The potential of halophytic grasses as fodder was also reported by Pasternak (1990), Barrett-Lennard (2003), Tomar et al. (2003), Bustan et al. (2005), Dagar and Singh (2007), Dagar (2018) and Ismail et al. (2019). Although less salt tolerant than species of *Atriplex*, *Distichlis spicata* ash content never exceeded 11% of the dry

Table 16.2 Yield of the perennial grasses irrigated with brackish and reclaimed water

Species	Irrigation water	Fresh biomass (Mg ha^{-1} month^{-1})	Dry biomass (%)	Dry biomass (Mg ha^{-1} month^{-1})
Sporobolus virginicus	Reclaimed	4·20 ± 2·18	66·87	2·81 ± 1·46
	Brackish	5·58 ± 2·68	45·88	2·56 ± 1·23
Pennisetum clandestinum	Reclaimed	7·19 ± 1·20	41·17	2·96 ± 0·49
	Brackish	9·92 ± 2·61	33·57	3·33 ± 0·88

The salinity of the brackish water ranged between 7 and 10 dS m^{-1}. The salinity of the reclaimed sewage was 2–3 dS m^{-1}

matter; about half of the amount was found in the salt-accumulating chenopods, highlighting its potential as a fodder crop (Bustan et al. 2005). The protein content of *D. spicata* varied widely between the accessions and ranged between of 9.2 and 18.9% of dry matter, similar to the protein content reported in *A. nummularia* (Pasternak 1990). Cultivation of *Leptochloa fusca* (Kallar grass) resulting in high productivity of 20 Mg ha^{-1} from 4 to 5 cuts per year (Mahmood et al. 1994) also improved the soil conditions (Hollington et al. 2001). The low salt secretion in grasses contributes to the maintenance of low leaf salt levels and relatively low Na/K ratios compared to that of dicotyledonous halophytes (Flowers and Colmer 2008). Liphschitz et al. (1974) reported the existence of active salt-secreting glands on the leaves of Rhodes grass (*Chloris gayana*), *Pennisetum clandestinum* and *Sporobolus virginicus*. Two salt-tolerant grass species were cultivated for their potential as salt-resistant ground cover and pasture plants with good nutritive properties (Table 16.2). Root, as well as shoot, growth decreased significantly when plants were irrigated with saline water, but no further reduction could be observed among all salt treatments ranging from 80 to 240 mm NaCl (Ventura et al. 2015).

Ahmad and Ismail (1993a, b) and Qadir et al. (2010) observed that certain species of fuel wood (some may also be lopped for forage) and worth grazing grasses and salt bushes show luxuriant growth at sandy strata when irrigated with saline water of oceanic strength. They found that in some trees like *Azadirachta indica*, *Casuarina equisetifolia* and *Eucalyptus camaldulensis*, 25% biomass reduction started only at ECiw >15 dS m^{-1} and in *Prosopis juliflora* at >20 dS m^{-1} while in *Tamarix articulata* only beyond 30 dS m^{-1} at sandy substrata. Among grasses, 25% yield reduction in *Sporobolus arabicus*, *Panicum turgidum* and *Thinopyrum ponticum* was observed only at EC_{iw} 10–15 dS m^{-1}, while in *Leptochloa fusca*, it was at ECiw 20 dS m^{-1}. The potential of forage biomass production of 32.3 Mg ha^{-1} by *Sesbania aculeata*, 24.6 Mg ha^{-1} by *Leptochloa fusca*, 22.6 Mg ha^{-1} by *Echinochloa colona* and 5.4 Mg ha^{-1} by *Eleusine coracana* in saline-sodic environment was reported, and these species helped in soil amelioration in terms of reducing soil pH and salinity and increasing nitrogen in the order *S. aculeata* > *L. fusca* > *E. colona* > *E. coracana*. Tomar et al. (2003) found that forage grasses like *Panicum laevifolium* and *P. maximum* were most suitable species producing annually 14–17 Mg ha^{-1} dry forage with saline irrigation showing their potential as silvopastoral grasses if grown in protected conditions.

Barrett-Lennard (2003) while describing the ecology and distribution of pasture species in Australia has reported several potential halophytic grasses and shrubs. Besides forage shrubs (*Atriplex*, *Halosarcia*, *Maireana*), many perennial grasses such as *Thinopyrum ponticum*, *Puccinellia ciliata*, *Paspalum vaginatum*, *Distichlis spicata*, *Pennisetum clandestinum*, *Sporobolus virginicus* and *Chloris gayana* have potential as halophytic forages. Some of the halophytes are good fodder and hence can be used for animal feeding (Ismail et al. 2019). However, some halophytes may cause nutritional barrier due to partially high salt content and antinutritional compounds (Khan et al. 2006). In one study on saline Vertisol, after 14 years of plantation, it was found that *Prosopis juliflora*, *Salvadora persica* and *Azadirachta indica* were most successful species for these soils. Among grasses, *Aeluropus lagopoides*, *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana*, *Dichanthium annulatum*, *Bothriochloa pertusa* and *Vetiveria zizanioides* and species of *Eragrostis*, *Sporobolus* and *Panicum* were found the most successful and form suitable silvopastoral system. Perennial grasses such as *Distichlis spicata*, *Paspalum vaginatum*, *Sporobolus virginicus* and *S. arabicus* could produce 17.6, 15.9, 18.4 and 12.3 Mg ha^{-1} oven-dry biomass, respectively, in Abu Dhabi Emirate, UAE, irrigating with saline water (Ismail et al. 2019). They also tried successfully many species of *Atriplex*, which produced 9.8–28.5 Mg ha^{-1} oven-dry forage biomass under saline environment.

16.3.2.3 Industrial, Medicinal and Other Uses

The utilization of halophytic plants as a source of renewable energy has emerged during the last decade (Rozema and Flowers 2008). Eshel et al. (2010, 2011) and Santi et al. (2014) working with two desert halophytic plants, *Tamarix jordanis* and *Euphorbia tirucalli*, for biomass production under extreme desert conditions reported that *T. jordanis* rich in cellulose and low hemicellulose and phenol contents is an ideal species for ethanol fermentation. *Tamarix aphylla* (erect type) trees produced 52 and 26 Mg ha^{-1} organic biomass when irrigated with reclaimed sewage (EC approx. 3 dS m^{-1}) or brine (EC approx. 7–10 dS m^{-1}), respectively. *Euphorbia tirucalli*, a desert succulent, was suggested as a potential biofuel crop (Nielsen et al. 1997; Calvin 1980). Dagar et al. (2012) studied the potentials of *Euphorbia antisyphilitica*, commonly known as Candelilla wax plant and is a succulent laticiferous potential hydrocarbon yielding petro-crop and found that it could yield 8–10% biomass utilized as bio-fuel. It can be grown successfully on degraded sandy and calcareous soils in arid and semi-arid regions. The crop, when irrigated with saline water, produced ~23 Mg ha^{-1} dry biomass in 2 years. Results also proved that the crop is a low-nutrient demanding crop as it required only 16 and 40 kg ha^{-1} of phosphorus and nitrogen, respectively, for optimum biomass production. It also requires less water and produced 17.5 and 15.25 Mg ha^{-1} dry biomass with saline water (12 dS m^{-1}) irrigation at Diw/CPE ratio of 0.1 and 0.2, respectively, as compared to 10.9 Mg ha^{-1} under rain-fed condition. For large-scale cultivation, it can be grown successfully on marginal calcareous and sandy soils of dry regions, and one or two life-saving irrigations with saline water will give optimum biomass. Jojoba (*Simmondsia chinensis*) is another potential perennial for dry region and is popular for its oil quality similar to sperm whale oil.

Cultivation of halophytes such as *Cyamopsis tetragonoloba* and *Simmondsia chinensis* holds promise mainly for their gums, oils and resins. *Balanites roxburghii* and *Calophyllum inophyllum* are good source of bioactive derivatives and considered essential ingredients for pharmaceuticals, agricultural pesticides, traditional medicines and natural cosmetics. Plant species like *Beta vulgaris*, *Leptochloa fusca* and *Jatropha curcas* have potential for renewable biofuels such as ethanol and biogas.

Some halophytes such as *Crithmum maritimum*, *Portulaca oleracea*, *Salicornia* spp. and *Aster tripolium* are edible (Simopoulos 2004; Tardio et al. 2006). These species are known for their ability to synthesize secondary metabolites that include simple and complex sugars, amino acids, quaternary ammonium compounds, polyols and antioxidants (e.g. polyphenols, β-carotene), ascorbic acid and ureides (Hasegawa et al. 2000; Ventura and Sagi 2013). Osmolytes can potentially be utilized in functional foods which possess disease-preventing and/or health-promoting benefits (Buhmann and Papenbrock 2013a). Such alternative crops may find niches in the demanding market for novelties while taking advantage of a range of saline irrigation water sources. Periwinkle (*Catharanthus roseus*) produces alkaloids useful in cancer treatments and can successfully be cultivated with saline irrigation.

Salvadora persica (miswak) is a non-traditional oilseed tree crop that is valuable for a wide variety of industries. The oil has a disagreeable odour that disappears on purification. The seed contains 40–45% of non-edible oil, is rich in lauric and myristic acids and is mainly used in soap and detergent industries. The salt tolerance of *Salvadora* has been widely studied, and its cultivation has been taken on coastal and inland saline soils (Gururaja Rao 2015; Gururaja Rao et al. 2003, 2017; Reddy et al. 2008). It is a good source for active ingredients like calcium, chloride and fluoride that help in promoting dental hygiene and health. Other than these three ingredients, miswak also contains good amounts of vitamin C, resins, tannins, silica, alkaloid and aromatic oils. Silica acts as abrasive material and helps in stain removal. Tannins offer astringent effect and stimulate premolar saliva production. Resins form protective layer over enamel and thus prevent caries. Alkaloids—salvadorine and trimethylamine—are active ingredients which offer antibacterial effects. Essential oils while offering mild taste act against bacteria, stimulate saliva and have carminative effect (Kumar et al. 2012).

Many crops of medicinal value have been cultivated successfully using saline water up to EC 10 dS m^{-1} in dry ecologies. These include *Plantago ovata*, *Cymbopogon flexuosus*, *Adhatoda vasica*, *Catharanthus roseus*, *Cassia senna*, *Lepidium sativum*, *Matricaria chamomilla*, *Aloe vera*, *Ricinus communis* and *Citrullus colocynthis* (Dagar 2014). All these are high value and potential crops. Many mangrove and associate species have very high potential for commercial exploitation: Nipa palm (*Nypa fruticans*) yields alcohol, *Cynometra iripa* yields seed oil of medicinal value, *Terminalia catappa* bear seed oil similar to almond, *Pandanus* gives essential oil of commercial importance and there are several species yielding products of ethno-biological and commercial value (Dagar et al. 1991; Dagar and Dagar 1999; Dagar and Singh 1999; Dagar 2018).

Most of the woody salt-tolerant tree species yield fuelwood used across the globe. Most useful genera include *Acacia*, *Albizia*, *Balanites*, *Cassia*, *Casuarina*, *Conocarpus*, *Eucalyptus*, *Leucaena*, *Pithecellobium*, *Parkinsonia*, *Prosopis*, *Salvadora*, *Sesbania*, *Tamarix*, *Terminalia* and almost all mangroves.

A diverse group of halophytes, from grasses to trees, have potential for landscaping and ornamental purposes and to improve aesthetic conditions under saline conditions; salt-tolerant lawn and turf grasses, cut flowers and landscape plants tend to increase the availability of freshwater for more essential applications. However, some of these decorative plants (*Acrostichum*, *Catharanthus*, *Causarina*, *Conocarpus*, *Eucalyptus*, *Hibiscus*, *Mairreana*, *Melalueca* and *Thespesia*) have been identified under their primary economic uses.

16.3.2.4 Halophytes in Bioremediation Programs

Phytoremediation is the cultivation of plants for the purpose of reducing soil and water contamination (by organic and inorganic pollutants) that results from the improper disposal of aquaculture, agriculture and industrial effluents. On salt-affected soils, phytoremediation is often the only effective and economical method of removing or reducing contaminates, particularly when covering large areas where physical/chemical treatments and leaching are too expensive or unfeasible. Bioremediation or bioreclamation of salt-affected soils is an economic solution mainly for developing countries since engineering options like drainage are expensive. Several authors (Ke-Fu 1991; Rabhi et al. 2009) have reported that the potential of halophytic plants to accumulate enormous salt quantities depends often on the capacity of their green biomass (hyper-accumulating plants). This ability could be of great importance, particularly in arid and semi-arid regions, where insufficient precipitations and inappropriate systems are unable to reduce the salt burden in the rhizosphere of plants (Shiyab et al. 2003). Environmentally safe and clean technique to address the salinity problem includes the introduction of salt (ion) removing species to control salinity and to maintain the sustainability of agricultural fields. Phytoremediation of coastal saline soils requires plants with high salt uptake rates, large biomass and high tolerance to a wide array of environmental conditions and constraints. Halophytic species thus could potentially create both environmental and economic solutions to remediate saline soils.

Salicornia cultivation may also confer economic benefits as the plants can be harvested for selenium-rich animal feed. A number of halophytic grasses have been proven to be effective in revegetating brine-contaminated soils that typically result from gas and oil mining. Eid (2011) showed the removal of Zn, Cu and Ni by *Sporobolus virginicus* and *Spartina patens* and found *Sporobolus* to be the more efficient. In many studies, *Leptochloa fusca* has been found to be an excellent grass for remediation of both sodic and saline soils (Dagar 2014). Cultivation of *L. fusca* enhanced leaching and interactions among soil chemical properties and thus restored soil fertility. It also fixes nitrogen in the soil. The soil maintained the improved characteristics with further growth of the grass up to 5 years suggesting that growing salt-tolerant plants is a sustainable approach to biological amelioration of saline wastelands.

Sesuvium portulacastrum is a salt hyper-accumulating halophyte which compartmentalizes the toxic Na^+ in the vacuoles and therefore membrane-bound transport system regulating cytosolic (Na^+, K^+ and Ca^{++}) and ion accumulation by increasing the vacuolar volume. This high salt-accumulating trait in its tissues may be exploited for reducing salt levels in the potential coastal saline soils by its continued cultivation. Studies by Ramaswamy et al. (2017) in coastal Tamil Nadu indicated the efficacy of this species to remove salt to a tune of 7.37 dS m^{-1} from the original 13.7 dS m^{-1} with in a span of 30 days after planting and 5.34 dS m^{-1} in 60 days after planting.

16.3.2.5 Restoration of Saline Soils Using Halophyte Sand Salt Mechanism

Case Study 1: Cultivation of Halophyte Salvadora Persica on Highly Saline Black Soils (ECe > 30 dS m^{-1})

Coastal and inland saline Vertisols in India pose serious threat to the economy of the region. For the management of moderate to highly saline coastal soils, agrotechnology [for cultivating economically important and salt-tolerant halophyte, *Salvadora persica* (Fig. 16.8), a facultative halophyte on coastal saline black soils of Gujarat state which is a potential source of seed oil], has been evolved. This species is a medicinal plant of great value, and its bark contains resins and an alkaloid called salvadoricine. The seeds are good source of non-edible oil and rich in C-12 and C-14 fatty acids having immense applications in soap and detergent industry (Gururaja Rao 1995, 2015). *Salvadora persica*, which is a large, well-branched evergreen shrub or small tree having soft whitish yellow wood with numerous branches and

Fig. 16.8 *Salvadora persica* on highly saline black soils: (**a**) left, just planted; and (**b**) right, 3-year-old plant

Table 16.3 Cost of cultivation of *Salvadora persica* on highly saline black soil (cost taken per hectare of plantation as in 2003)

Field operations (input costs)	Cost (₹)
Field preparation (by tractor)	500
Pitting (625 pits of 30 cm × 30 cm × 30 cm)	625
Cost of saplings at ₹ 0.90 per plant	565
Planting	50
Irrigation during first year (saline water)	150
Digging of pit of 2.5 m × 2.0 m × 1 m (for saline water)	300
Fertilizer (at 50 g DAP per plant) and FYM	300
Plant basin making at ₹0.35 per plant	220
Miscellaneous (gap filling at 5%)	50
Total	2760

Source: Gururaja Rao et al. (2003)

Table 16.4 Seed production and economic returns of *Salvadora* plantation on highly saline black soils (ECe > 55 dS m^{-1})

Year	Seed yield (Mg ha^{-1})	Returns (₹ha^{-1})		Cost/benefit ratio
		Gross	Net	
I Year	Nil	Nil	Nil	Nil
II Year	0.725	3625	365	10.03
III Year	0.978	4890	4340	0.13
IV Year	1.58	7900	7250	0.09
V Year	1.838	9190	8440	0.09

Source: Gururaja Rao et al. (2003)

drooping, glabrous and shining, has the potential of regreening the highly saline soils that cannot be put under arable farming.

Studies indicated that the saplings could be raised using saline water of 15 dS m^{-1}, which is an advantageous feature in areas with limited availability of freshwater. The cost of cultivation including raising of nursery came to ₹2760 per ha in the first year (Table 16.3). By the fifth year, the plants would yield about 1800 kg ha^{-1}, with net returns of ₹8400 per ha. This species, thus, while giving economic returns on costal saline black soils with salinity up to 50 dS m^{-1}, also provides ecorestoration through environmental greening and forms a niche for highly saline black soils (Table 16.4; Fig. 16.9; Gururaja Rao et al. 2003). A spacing of 4 m × 4 m has been found ideal for planting on saline black soils (Gururaja Rao et al. 2001a, 2004a, b).

Studies conducted at CSSRI, Bharuch, Gujarat, on *Salvadora persica* indicated that the plant is a candidate for highly saline Vertisols with salinity up to 45–55 dS m^{-1}. The National Bank for Agriculture and Rural Development (NABARD) along with CSSRI had come out with a bankable model for cultivation

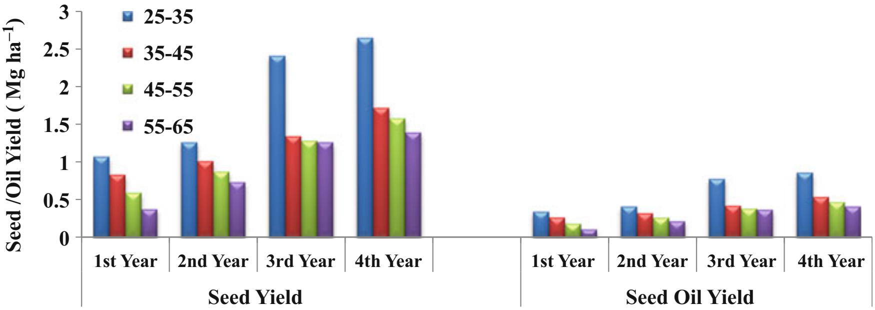

Fig. 16.9 Seed and seed oil yield in *Salvadora persica* grown at different soil salinities (ECe dS m^{-1})

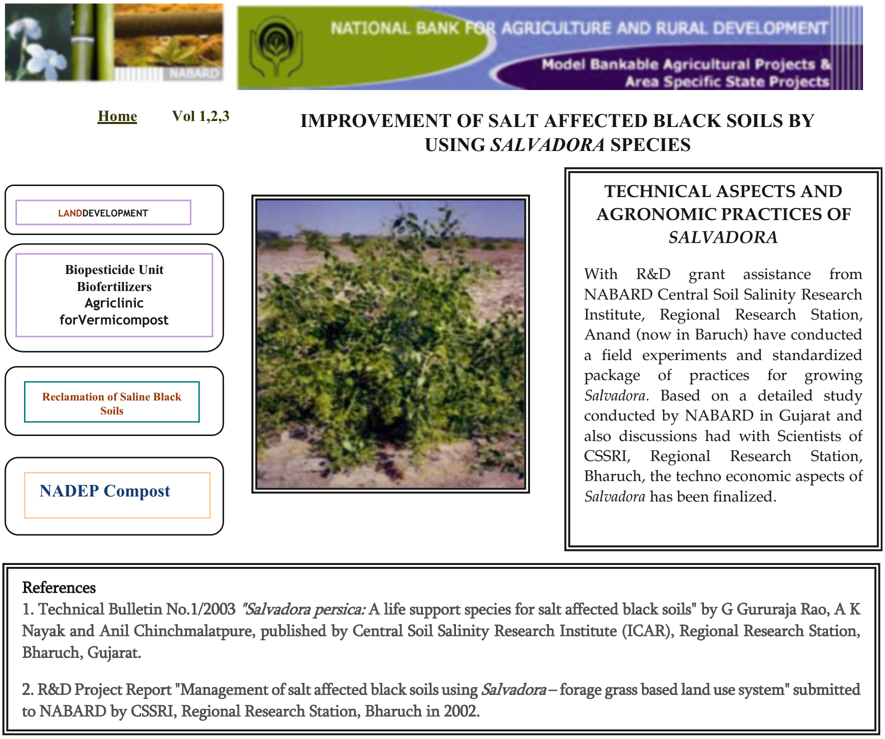

Fig. 16.10 Bankable model for cultivation of *Salvadora persica* developed by NABARD and CSSRI, Bharuch, Gujarat, India

of *Salvadora persica* on saline Vertisols (Fig. 16.10) under the Refinancing Module. Planting of *Salvadora persica* fetch about ₹7000 per ha from highly degraded land. Apart from this, the species provides a dwelling place for birds and other animals, thus enhancing the environmental greening and biodiversity.

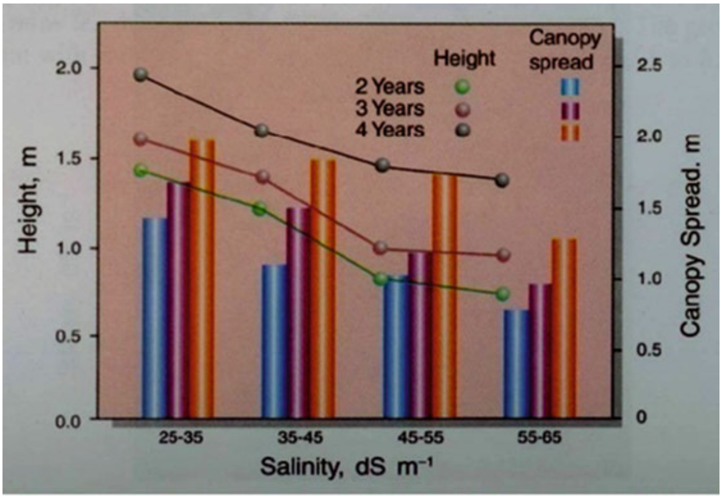

Fig. 16.11 Growth of *Salvadora persica* on saline black soils of Gujarat at different salinities

Growth and Physiology of *S. persica*

The data in Fig. 16.11 reveal that although there is reduction in height and canopy spread with increasing salinity, the growth and seed yield (Fig. 16.9) is quite promising and sustainable even at high salinity. Soil salinity under the plantation has been found reduced by fourth year resulting in the possibility intercropping with less tolerant crops/forages. Greening with plants helps to win back several bird species as the trees provide a dwelling place for them (Gururaja Rao et al. 2003; Maggio et al. 2000).

Salt Compartmentation

Distribution of sodium and chloride ions (Fig. 16.12) studied in different plant parts of *S. persica* growing at different in situ salinities indicated bark and senescing leaves as the potential sinks for toxic ions like Na^+ and Cl^-, thereby sparing other plant parts like immature leaves and partially mature and physiologically mature leaves to perform their normal physiological activity that enables the plants to remain lush green even at high salinity. Further, senescing leaves act as potential sinks for toxic ions that reduce the load on other photosynthesizing tissues which remain by and large salt-free (Gururaja Rao et al. 1999a, b, 2003).

Na^+ and Cl^- Concentration and Flux

The rate and ion transport (flux) from root to shoot and to whole plant was calculated using the formula $Js = (Ms_2 - Ms_1) \times (WR_2/WR_1/(t_2 - t_1)(WR_2 - WR_1)$, where Js is the rate of transport (flux), Ms_1 and Ms_2 are the amounts of ion in the shoot/whole plant and WR_1 and WR_2 are the fresh weights of the roots at the harvest times t_2 and t_1 (Pitman 1975).

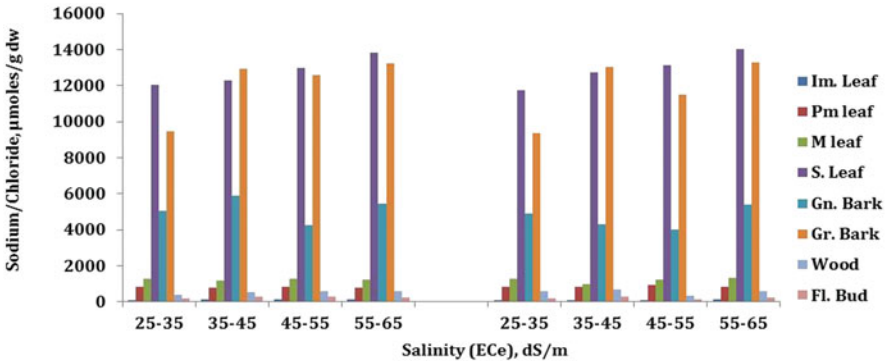

Fig. 16.12 Compartmentation of sodium and chloride in *Salvadora persica* grown at different salinities on highly saline black soil

Concentration of sodium and chloride in plant parts indicated maximum amount of Na^+ and Cl^- ions in the bark, root and senescing leaves (Table 16.5). These tissues act as potential sink for excess Na^+ and Cl^- ions. The capacity of the sink increased with age of the plant as well as increase in salinity which indicates that *S. persica* has well-developed salt compartmentation mechanism (Gururaja Rao et al. 2004b). Though Na^+ concentration increases with increase in salinity, the total Na^+ uptake showed a decreasing trend which may be obviously due to decrease in the biomass yield with increase in salinity. Similarly, chloride uptake in root is much higher than that of the shoot. The rate of flux of Na^+ and Cl^- ions to the whole plant while increased with increase in salinity showed a decreasing trend with age (Table 16.6). The flux of these ions from root to the shoot was a fraction of that to the whole plant indicating that roots accumulate more ions than shoots. In this species, roots act as both Na^+ and Cl^- accumulator.

Soil Salinity Under Plantations

The soils of studied site are grouped as deep, clay loam, hyperthermic and montmorillonitic family of Vertic Haplustepts and showed high degree of spatial and temporal variation in soil salinity initially ranging from 65 to 70 dS m^{-1} in the top layer. Salinity of the soil decreased with depth, i.e. from surface to 90 cm depth (Fig. 16.13). Cultivation of *S. persica* up to 5 years resulted in slight decline in soil salinity as compared to the pre-planting salinity. Changes in surface salinity are partly attributed to the ability of plants to extract the salt and partly due to root activity which improves the physical properties of the soil. However, the magnitude of fluctuation in salinity was not much at lower layers. The groundwater table might be contributing to salinity causing only minor changes at lower depths. The spatial variability of surface salinity under 5-year-old plantation (Fig. 16.14) showed significant difference from the initial salinity prior to planting.

Table 16.5 Concentration of Na^+ and Cl^- (per cent) ions in different plant parts of *Salvadora persica* grown on highly saline soil

	Salinity range (dS m^{-1})											
	25–35			35–45			45–55			55–65		
Plant part	Second year	Third year	Fourth year	Second year	Third year	Fourth year	Second year	Third year	Fourth year	Second year	Third year	Fourth year
Na^+												
Root	1.13	1.62	1.86	1.61	2.11	2.30	1.91	2.37	2.57	1.93	2.39	2.60
Wood	0.02	0.03	0.03	0.03	0.04	0.04	0.03	0.04	0.05	0.04	0.06	0.06
Bark	1.59	1.72	1.95	2.12	2.29	2.60	2.33	2.52	2.86	2.73	2.95	3.34
Im. Leaf	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03
M. leaf	0.18	0.18	0.21	0.19	0.20	0.23	0.21	0.22	0.25	0.22	0.24	0.27
S. leaf	1.66	1.81	2.06	2.11	2.30	2.61	2.30	2.38	2.71	2.39	2.51	2.83
LSD $p = 0.05$	0.36	0.13	0.18	0.46	0.21	0.22	0.89	0.16	0.30	0.69	0.46	0.71
Cl^-												
Root	2.13	2.65	2.70	2.65	3.36	3.60	2.88	3.00	3.90	2.94	4.00	4.01
Wood	0.04	0.05	0.06	0.05	0.06	0.06	0.05	0.07	0.07	0.07	1.00	0.10
Bark	2.49	2.69	3.05	3.43	3.70	4.01	3.74	4.04	4.41	4.26	4.62	5.14
Im. Leaf	0.03	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.5	0.05	0.06
M. leaf	0.28	0.29	0.32	0.31	0.31	0.38	0.33	0.34	0.39	0.35	0.40	0.42
S. leaf	2.63	2.82	3.19	3.17	3.67	2.71	3.58	3.76	4.23	3.58	4.04	4.59
LSD $p = 0.05$	0.40	0.16	0.39	1.05	0.28	0.30	0.58	0.22	0.40	0.95	0.98	0.83

Im immature, *M* mature, *S* senescing leaves

Table 16.6 Uptake and flux of Na^+ and Cl^- ions in *S. persica* on saline black soils

	Uptake (g)				Flux (μg g^{-1} d^{-1})			
	Shoot		Root		Shoot		Root	
Salinity class (dS m^{-1})	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-
	Second year							
25–35	6.44	10.18	8.40	15.86				
35–45	5.12	8.53	9.31	15.29				
45–55	4.10	6.57	6.58	9.91				
55–65	3.68	5.64	4.97	7.56				
LSD ($p \leq 0.05$)	1.21	1.88	1.93	2.12				
	Third year				Between third and second year			
25–35	16.01	25.90	27.36	44.93	29.9	46.1	9.8	16.2
35–45	14.21	22.95	27.69	44.08	39.0	61.3	12.9	20.4
45–55	10.13	16.21	18.56	29.43	50.2	81.3	16.8	26.9
55–65	9.82	15.59	13.62	22.84	78.8	131.4	19.5	52.6
LSD ($p \leq 0.05$)	2.11	2.88	3.58	5.35	10.5	13.8	4.3	5.8
	Fourth year				Between fourth and third year			
25–35	22.31	34.71	38.33	56.66	10.8	12.9	3.9	5.5
35–45	18.42	28.69	37.64	58.73	12.3	17.8	3.7	5.0
45–55	14.43	22.30	37.23	37.23	17.8	23.5	7.3	9.7
55–65	13.51	20.84	29.35	29.35	29.7	410.2	11.9	16.9
LSD ($p \leq 0.05$)	3.95	4.23	0.53	1.88	1.88	3.50	1.20	1.70

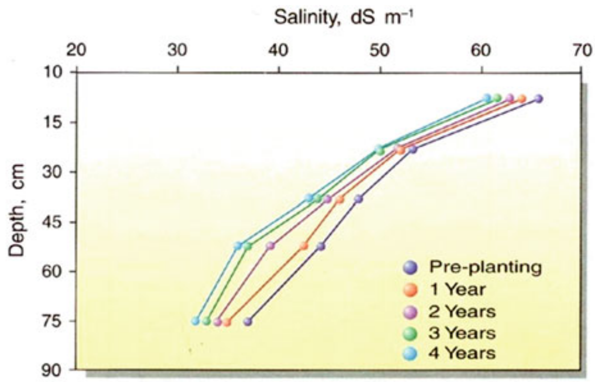

Fig. 16.13 Soil salinity variations over the years under *S. persica* grown on highly saline black soil (55–65 dS m^{-1} range)

Case Study 2: Forage Grasses for Restoring of Coastal Saline Vertisols of Gujarat

Agriculture and animal husbandry in India are interwoven as mixed farming, and livestock rearing forms an integral part of rural living. India supports nearly 20% of the world's livestock. Most often and especially in arid and resource-poor regions, livestock is the only source of cash income for subsistence farms. It insures some livelihood in the event of crop failure. At present, India faces a net deficit of 61.1% green fodder, 21.9% dry crop residues and 64% feeds. Due to ever-increasing

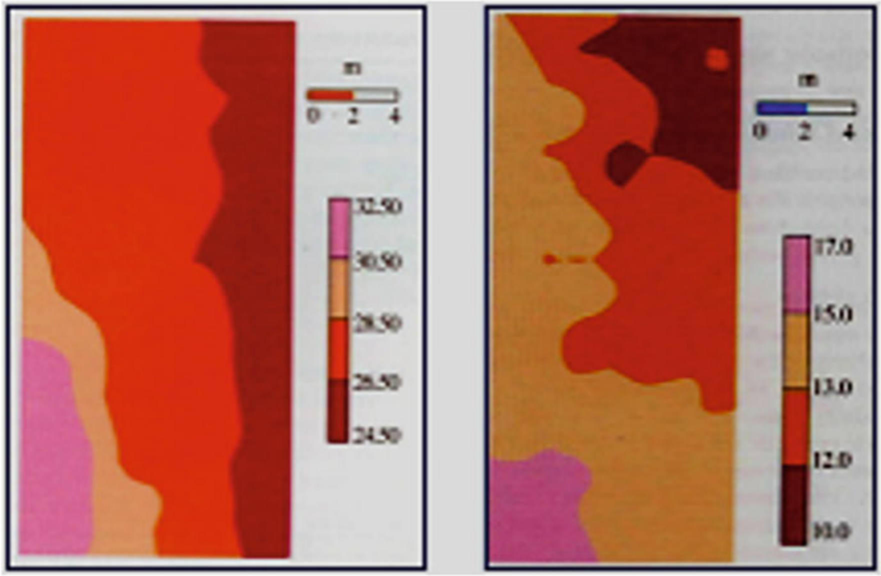

Fig. 16.14 Spatial variability in soil salinity prior and after planting of *S. persica*

population pressure, arable land will mainly be used for food and cash crops, leaving little chance of having good-quality arable lands for fodder production. Therefore, poor-quality saline/sodic lands provide a good avenue to increase availability of fodder using suitable grasses which can be cultivated in saline/sodic environment. Many forage grasses such as *Leptochloa fusca*, *Cynodon dactylon*, *Dactyloctenium sindicum*, *Paspalum vaginatum*, *Chloris gayana*, *Echinochloa turnerana*, *E. colonum*, *Eragrostis tanella*, *Dichanthium annulatum*, *D. caricosum*, *Brachiaria mutica* and species of *Panicum* are the predominant in coastal saline soils (Dagar 2005; Dagar and Singh 2007; Dagar et al. 2014). Forage grasses like Kallar grass (*Leptochloa fusca*), Rhodes grass (*Chloris gayana*) and Para grass (*Brachiaria mutica*) are highly salt tolerant and high biomass yielders. While *Prosopis juliflora*-Kallar grass system has been found highly promising for firewood and forage production on sodic soils (Singh 1995; Singh and Dagar 2005). *Salvadora persica* with Kallar grass and/or *Dichanthium annulatum* has been found ideal for saline Vertisols (Gururaja Rao 2004). Singh and Dagar (1998, 2005) and Singh et al. (1993, 2014) reported a silvopastoral system comprising *Prosopis* with Kallar grass to be ideal and highly remunerative in the early 4 years on highly sodic soil. Tree species like *Acacia nilotica*, *Eucalyptus tereticornis* and *Parkinsonia aculeata* on ridges and Kallar grass in trenches have been found ideal (Grewal and Abrol 1989; Dagar et al. 2001). Performance of Kallar grass in furrow system has been found beneficial on saline Vertisols (Gururaja Rao et al. 2001b, 2005, 2011). Agrotechnology for the cultivation of forage grasses, *Dichanthium annulatum* and *Leptochloa fusca* (in salinity of 8–10 dS m^{-1}) and *Eragrostis* and *Aeluropus*

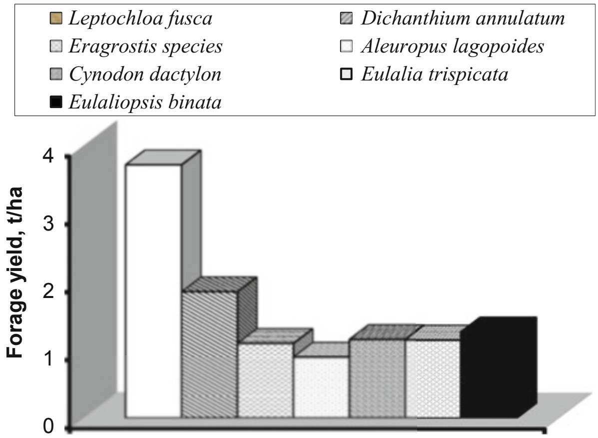

Fig. 16.15 Forage yield of grasses on saline black soils (ECe, 14.6 dS m^{-1}). Source: Gururaja Rao et al. (2001a)

Table 16.7 Utilization of Kallar grass for biogas production

Material	Yield (ha^{-1} $year^{-1}$)
Kallar grass	40 Mg (green)
Kallar grass	16.8 Mg (dry)
Methane (0.18 m^3 kg^{-1} dry biomass)	3024 m^3
Sludge (0.72 kg kg^{-1} dry matter)	12.1 Mg
Nitrogen in sludge	240 kg
Total energy	15×10^6 kcal

Source: Malik et al. (1986)

lagopoides, on saline black soils having salinity up to 14–16 dS m^{-1} have been evolved. Application of nitrogen at 46 kg ha^{-1} as urea increased the forage yield by about 70% in *Dichanthium annulatum* (Gururaja Rao et al. 2001a).

Other grasses like *Aeluropus lagopoides* and *Eragrostis* species are ideal for cultivation on highly saline black soils. *Dichanthium annulatum* is another grass with better forage qualities and high slat tolerance (Fig. 16.15; Gururaja Rao et al. 2001a). This species has a well-defined salt compartmentation in that roots act as potential sinks for toxic ions like Na^+ and Cl^- making the shoots relatively salt-free.

Kallar grass actually thrives in sodic and waterlogged soil conditions and has been used in their reclamation. Studies conducted on moderately saline black soils with salinity of 14–18 dS m^{-1}, under ridge and furrow system of planting, indicated that this grass was found to yield well when planted in furrows (Gururaja Rao et al. 2001a, 2012a, 2017). This grass apart from its use as fodder also is used as a substrate for biogas production; the energy yield per hectare is estimated to be 15×10^6 kcal (Table 16.7; Malik et al. 1986).

Dichanthium annulatum and *Leptochloa fusca* in a ridge-furrow planting system with 50 cm high ridge and 1 m between midpoints of two successive ridges were found ideal in saline Vertisols having salinity up to 8–10 dS m^{-1}. For maximizing forage production on these soils, *Dichanthium* on ridges and *Leptochloa* in furrows form ideal proposition. Nitrogen given at the rate of 45 kg ha^{-1} (in the form of urea)

Table 16.8 Growth and yield of forage grasses under ridge and furrow planting system

Grass species	Height (m)		Tiller (plant^{-1})		Green forage yield (Mg ha^{-1})	
	Ridge	Furrow	Ridge	Furrow	Ridge	Furrow
Leptochloa fusca	1.18	1.02	10.62	9351	3.17	3.73
Dichanthium annulatum	0.91	0.74	6.41	5.32	1.85	1.76
LSD ($p \leq 0.05$)		Height		Tillers		Yield
Planting method		0.12		0.91		NS
Grass species		0.16		1.53		0.82
Planting method × grass species		NS		2.24		NS

Salinity of the saturation extract (0–30 cm): 15.4 dS m^{-1}
Source: Gururaja Rao et al. (2001a)

Table 16.9 Effect of nitrogen on growth and forage yield (Mg ha^{-1}) of forage grasses

Grass species	Height (m)		Tiller (plant^{-1})		Green forage yield (Mg ha^{-1})	
	$^{+}$N	$^{-}$N	$^{+}$N	$^{-}$N	$^{+}$N	$^{-}$N
Leptochloa fusca	1.39	0.99	12.54	4.46	3.21	2.13
Dichanthium annulatum	1.01	0.87	10.24	7.38	2.24	1.32
LSD ($p \leq 0.05$)		Height		Tillers		Yield
Planting method		0.13		3.11		0.88
Grass species		0.22		2.32		0.55
Planting method × grass species		NS		NS		NS

Source: Gururaja Rao et al. (2001a)

at the time of rooted slip planting boosts forage production and improves forage quality traits. *Dichanthium annulatum* has been found most suitable for saline black soils, as it possessed well-defined salt compartmentation, wherein the roots act as potential sinks for toxic ions like sodium and chloride, making the shoot portions relatively salt-free (Table 16.8; Gururaja Rao et al. 2001a, 2017).

Studies on forage grasses on saline Vertisols further revealed the presence of well-defined salt exclusion mechanism and osmotic adjustment in *Dichanthium annulatum* which makes it salt tolerant. *Leptochloa fusca* also gave maximum forage yield. Application of nitrogen when grown in furrows at 46 kg ha^{-1} as urea increased the forage yield by about 70% (Table 16.9) in *Dichanthium annulatum* (Gururaja Rao et al. 2001a). The cattle and camel populace form the important livestock of the region. Cultivation of salt-tolerant grasses like *Dichanthium annulatum* and *Leptochloa fusca* on moderate saline soils results in 1.9 and 3.2 Mg ha^{-1}, respectively.

Halophytic forage grasses, viz. *Aeluropus lagopoides* and *Eragrostis*, have been found to be ideal for saline agriculture on saline black soils. Of these two, *Aeluropus* was found to possess better forage qualities and salt removal ability from the soils. These grasses responded well to saline water up to 30 dS m^{-1} and thus form suitable

Table 16.10 Uptake and flux of Na^+ and Cl^- ions in *Aeluropus lagopoides* under saline water irrigation

Salinity (dS m^{-1})	Uptake (g)				Flux (μg g^{-1} day^{-1})			
	Shoot, root				To whole plant, to shoot			
	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-
	First week							
10	3.91	4.37	5.42	5.14				
20	3.64	4.12	4.86	4.58				
30	3.42	3.90	4.39	4.32				
40	3.08	3.76	4.14	4.24				
	Second week				Between first and second week			
10	4.78	4.36	5.96	4.35	7.90	9.92	2.18	3.42
20	4.32	4.04	5.78	4.14	8.62	10.42	3.62	3.75
30	4.02	3.92	4.14	3.62	9.36	12.62	3.92	4.62
40	3.64	3.51	4.04	3.44	10.42	18.80	4.14	5.96
	Third week				Between second and third week			
10	4.92	4.88	5.84	4.98	10.39	12.82	3.14	4.36
20	4.81	4.64	5.72	4.86	13.86	16.01	3.36	5.62
30	4.32	4.38	4.92	4.64	15.14	22.41	3.92	6.98
40	4.02	4.14	4.44	4.32	19.52	24.62	4.79	9.39
	Fourth week				Between third and fourth week			
10	5.64	5.84	6.10	5.14	15.76	19.72	3.79	4.72
20	4.92	4.92	5.72	5.02	16.80	25.6	5.16	6.72
30	4.84	4.63	5.32	4.84	18.44	26.8	6.13	8.42
40	4.12	4.24	4.79	4.36	26.12	28.42	7.14	8.92

for cultivation on coastal saline Vertisol with plenty of saline groundwater resources (Ahmed et al. 2011; Gururaja Rao et al. 2005, 2011).

Salt Uptake and Ion Flux

The leaf and stem ions, i.e. Na^+ and Cl^-, increased with the increase in salinity in these grasses. The shoot (leaf and stem) sodium content after two irrigations increased from 2000 to 5900 μmol in leaf of *Eragrostis* sp. and 3500–100 μmol in *Aeluropus lagopoides*. In stem, the Na^+ and Cl^- contents were higher when compared to the leaves indicating stem as a potential sink. Among the grasses, Na^+ and Cl^- contents were found to be more in *Aeluropus lagopoides* than *Eragrostis* sp. (Ahmed et al. 2011; Gururaja Rao 2015; Gururaja Rao et al. 2005, 2011). Uptake and flux of Na^+ and Cl^- and the total Na^+ uptake showed a decreasing trend with increase in salinity of irrigation water in both the grasses. *Aeluropus lagopoides* showed higher uptake than that of *Eragrostis* spp. though the increase was only marginal (Tables 16.10 and 16.11). The total Na^+ content is less in shoot than in the root in both the grasses irrespective of salinity and age of the plant. Chloride uptake, however, is relatively more in root than in shoot. The rate of flux of Na^+ and Cl^- to the whole plant though increased with salinity and age of the plant.

Table 16.11 Uptake and flux of Na^+ and Cl^- ions in *Eragrostis* species under saline water irrigation

Salinity (dS m^{-1})	Uptake (g)				Flux (μg g^{-1} day^{-1})			
	Shoot, root				To whole plant, to shoot			
	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-
	First week							
10	4.20	4.85	5.82	5.13				
20	3.92	4.60	5.20	4.93				
30	3.61	4.05	4.85	4.14				
40	3.40	3.70	3.85	3.96				
	Second week				Between first and second week			
10	5.15	4.74	6.40	4.68	8.78	1.88	2.42	3.62
20	4.95	4.44	6.00	4.53	9.92	13.84	3.03	4.81
30	4.45	4.10	5.28	3.96	12.62	14.09	3.84	4.99
40	3.62	3.78	4.62	3.65	13.12	26.32	4.12	8.92
	Third week				Between second and third week			
10	5.60	5.66	6.78	5.25	13.42	16.24	3.62	5.14
20	5.05	5.05	6.18	4.94	17.32	20.33	5.14	6.24
30	4.62	4.60	5.85	4.60	18.92	28.75	5.92	8.36
40	4.28	4.20	4.90	4.28	24.32	32.48	7.96	10.62
	Fourth week				Between third and fourth week			
10	6.05	6.20	6.90	6.18	19.70	26.78	6.32	8.32
20	5.25	5.00	6.23	5.54	26.30	32.14	8.44	10.64
30	5.05	5.05	5.63	4.84	28.15	39.36	9.63	14.20
40	4.60	4.60	5.00	4.12	30.10	42.74	10.40	16.32

Table 16.12 Ion partitioning in halophytic grasses grown on saline Vertisols

Part of the plant	*Aeluropus lagopoides*			*Eragrostis* species		
	Na^+	K^+	Na/K	Na^+	K^+	Na/K
Inflorescence	2.6	4.4	0.590	4.3	4.9	0.876
Mature foliage	12.4	8.8	1.409	11.6	7.6	1.526
Stem	16.1	10.4	1.548	12.4	7.9	1.570
Old foliage	13.6	7.9	1.722	14.2	7.4	1.972
Root	30.2	8.8	3.432	29.4	9.1	3.231

Salt Compartmentation and Salt Budgeting

Studies on ion uptake, partition and ion flux (Table 16.12) indicated that roots act as potential sinks for toxic ions like Na^+ and Cl^-. *Aeluropus* showed higher ion uptake than *Eragrostis*. While roots of *Aeluropus* showed 65.4% uptake of total salt, the shoots showed only 34.6% and in *Eragrostis* roots retained 70.6% salt and shoots only 29.4%. This lower ion salt content in the shoots reduces the salt toxicity to the photosynthesizing tissue and also helps in forage quality. Ion partitioning (Na^+ and Cl^-, Table 16.12) in shoot and roots of two grasses indicated that roots do act as sinks for these toxic ions when plants attain maturity. The grasses have been found

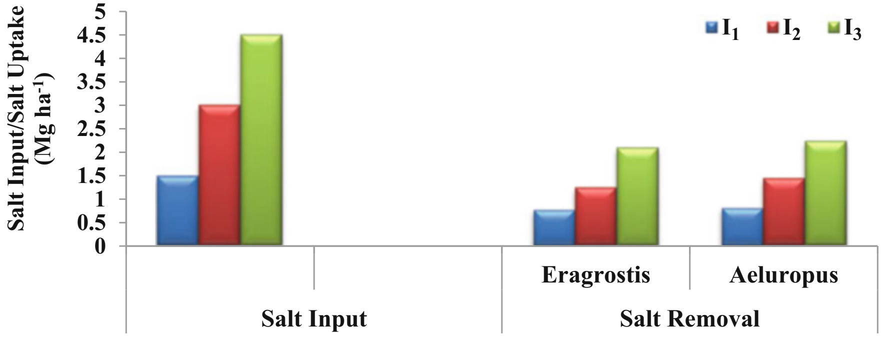

Fig. 16.16 Salt input and salt uptake by forage grasses under saline water irrigation on saline Vertisols (I_1, I_2 and I_3 indicate 1, 2 and 3 number of irrigations, respectively)

very effective in salt removal from the soil layers. *Aeluropus* was found to remove more salt than *Eragrostis*.

Ion compartmentation at organ level indicated higher amount of sodium in roots followed by stem and old leaves and the least in inflorescence in both the grasses. Similar trend was observed in potassium in that foliage and roots had higher potassium than inflorescence (Table 16.12). Higher accumulation of sodium in roots, old leaves and stems indicates the physiologically mature foliage had relatively low tissue sodium. Of the two forage grasses, *Aeluropus* had higher potassium in foliage while *Eragrostis* had higher potassium in roots. Contrary to this, sodium was found to be more in the foliage of *Eragrostis*, while roots of *Aeluropus* had marginally higher sodium. Once the flowering occurs, higher sodium is found to be more in older leaves in *Eragrostis*, when compared to *Aeluropus*, while older leaves showed lesser sodium when compared to shoot (Gururaja Rao et al. 2011).

Salt Removal

Salt budgeting including contributions of saline water, subsurface salinity and the salt uptake by the halophytic grasses indicated that *Aeluropus* had better salt removal, i.e. 43.9% when compared to *Eragrostis* with 39.7% (Fig. 16.16). This feature is highly useful in using these grasses under saline agriculture programs for lowering soil salinity in coastal saline soils, which over the years will help cultivation of lesser tolerant and more economically potential species.

Production

Green forage yield of these grasses under field conditions is given in Fig. 16.17, which indicated higher forage yield in *Eragrostis* sp. when compared to *Aeluropus lagopoides* at a salinity of 14.6 dS m^{-1}. *Eragrostis* sp. showed higher fresh and dry plant biomass than *Aeluropus lagopoides* (Table 16.13). Among the treatments, *Eragrostis* did not show much variations in the fresh and dry shoot biomass, whereas *Aeluropus lagopoides* showed distinguishing variation in these parameters indicating the higher tolerance of *Eragrostis* sp. The root biomass was, however,

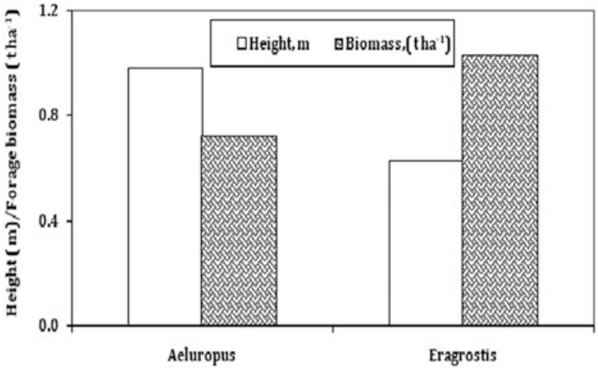

Fig. 16.17 Height and biomass yield in *Aeluropus lagopoides* and *Eragrostis* sp. grasses at a soil salinity of 14.6 dS m^{-1} in field conditions

Table 16.13 Plant biomass (g $plant^{-1}$) of halophytic grasses irrigated with saline water

ECe (dS m^{-1})	*Eragrostis* spp.				*Aeluropus lagopoides*			
	Shoot		Root		Shoot		Root	
	Fr. Wt.	Dr. Wt	Fr. Wt.	Dr. Wt	Fr. Wt.	Dr. Wt	Fr. Wt.	Dr. Wt
10	21.39	10.93	11.23	5.21	13.95	7.42	5.27	2.64
20	19.75	9.83	11.74	5.33	11.41	6.94	7.10	3.60
30	18.31	9.17	13.37	6.42	10.69	6.36	8.64	4.33
40	17.04	8.47	17.38	8.99	8.67	4.87	9.06	4.84
LSD ($p \leq 0.05$)	1.00	0.94	2.09	1.11	0.87	1.20	1.98	1.21

found to be more at higher salinity in both the grasses, indicating that the roots of these grasses showed more tolerance than shoots. This is also clearly evident from the shoot/root biomass ratios of both the grasses. The increase in salinity resulted in decrease in shoot biomass indicating an inverse relation between salinity and biomass production as reported earlier by Gururaja Rao et al. (2011).

Working with *Eragrostis*, Asfaw and Danno (2011) reported that tef varieties are most affected by salinity than tef accessions. Forage quality was highest when *A. lagopoides* was in the vegetative stage and tended to decrease sharply as the plant matured towards the seed ripening stage (Rad et al. 2013). Increase in the forage quality with increase in salinity of irrigation water was noticed in both the grasses which indicated their higher production potential at higher salinity. Higher ash content of *Aeluropus lagopoides* can be ascribed to higher mineral uptake as reported in other grasses as well. Similar studies with *A. lagopoides* on its efficacy for regreening of saline lands were carried out in Pakistan (Gulzar et al. 2003; Ahmed et al. 2011).

Effect of Nitrogenous Fertilizer on Growth and Forage Yield

Nitrogen applied at 60 kg ha^{-1} has boosted the growth and biomass production (Table 16.14). However, no significant differences were noticed when the grasses

Table 16.14 Effect of nitrogen on forage biomass of halophytic grasses irrigated with saline water

	Aeluropus lagopoides			*Eragrostis* species		
Irrigation	N0	N30	N60	N0	N30	N60
I_1	1.01	1.24	1.29	1.12	1.25	1.34
I_2	1.10	1.28	1.36	1.19	1.28	1.41
I_3	1.15	1.31	1.41	1.22	1.31	1.44
LSD ($p \leq 0.05$)						
Nitrogen	0.18			0.08		
Irrigation	0.09			0.12		
N × I	0.11			0.11		

I_1, I_2 and I_3 indicate irrigation after 10, 20 and 30 days' intervals, respectively

were irrigated at 15 and 30 days' interval, indicating by giving the grasses irrigation once in 30 days, saline water can be saved by 50%; thus, in the water-scarce regions, this becomes handy for taking up other halophytes/salt-tolerant plants for saline agriculture programs. Nitrogen given at 60 kg ha^{-1} though slightly enhanced forage yield with three irrigations when compared to two irrigations, and by forgoing this forage loss, saline water can be saved up to 33%.

Application of nitrogen has been found to enhance forage biomass and also the salt uptake from the soil. Moreover, nitrogen being the most limiting nutrient for crop production on saline Vertisols that are low in N and organic matter when given with saline water resulted in significant increase in forage yield of both the grasses. Of the two, *Eragrostis* was found to have higher growth, tillers and forage yield with 60 kg ha^{-1} N application when saline water was applied at 15 days' interval. The grasses were found very effective in salt removal from the soil layers, *Aeluropus* removing more salt than *Eragrostis*. Analysis of tissue sodium and chloride indicated their content per se decreased when compared to those given no nitrogen. This low tissue sodium and chloride, however, improved the forage quality parameters. Nitrogen given at 60 kg ha^{-1} resulted in lowered tissue ion content, resulting mainly from the increased biomass which resulted in lowered salt distribution per unit weight of the tissue.

Forage Quality

Leaf protein content was found to be more in *Aeluropus lagopoides* than *Eragrostis* in all the salinity treatments. With increase in salinity, a decrease in protein content was noticed in both the grasses. The shoots showed higher sugar content in *Aeluropus lagopoides* than *Eragrostis* which was found to increase with salinity in plants irrigated with 30 dS m^{-1} saline water. However, under 40 dS m^{-1} saline water irrigation, both the grasses showed reduced sugars as compared to 30 dS m^{-1}. Proline content also followed the trend of the protein; it increased from 10 to 40 dS m^{-1} in both grasses. Higher proline as noticed at higher salinities coupled with higher tissue Na^+ helps in osmoregulation and thus turgor regulation leading to better growth. Crude fibre and ash contents of the halophytic grasses (shoots) indicated that *Aeluropus lagopoides* showed higher fibre and ash content when

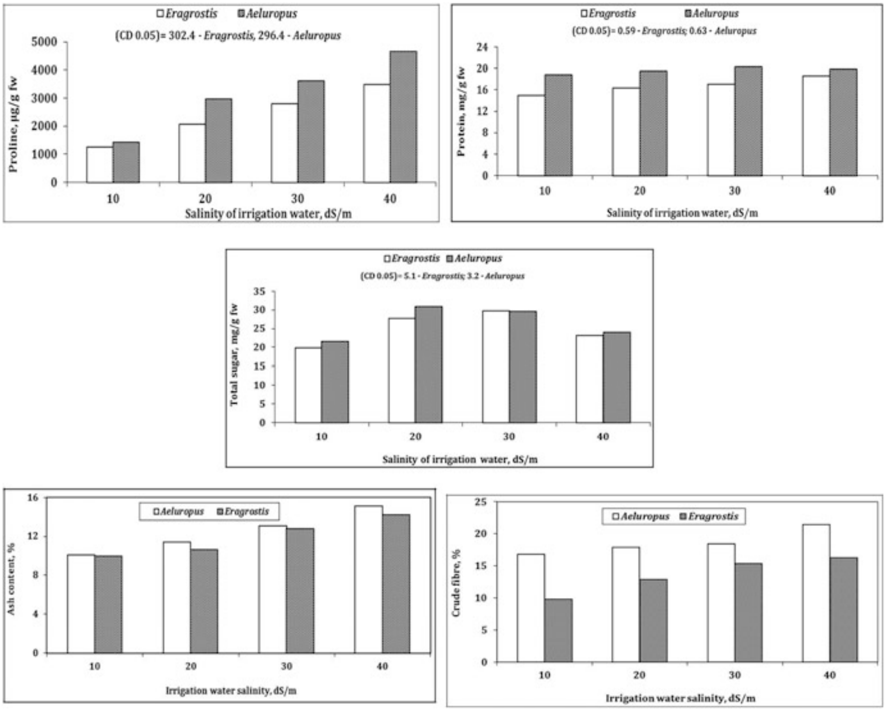

Fig. 16.18 Effect of saline water irrigation on forage quality of halophytic grasses

compared to *Eragrostis*. Crude fibre, a mixture of cellulose, hemicellulose and lignin, gives strength. Higher ash content of *Aeluropus lagopoides* can be ascribed to higher mineral uptake as reported in other grasses (Fig. 16.18).

16.4 Halophytes in Biosaline Agroforestry

Biosaline agriculture is prospective new area of research where the genetic resource of halophyte and salt-tolerant plant could be utilized for producing human and animal diet. Biosaline agriculture involving trees and animals mainly livestock (agroforestry) in present scenario of land degradation and climate change is of great importance. Saline agroforestry is capable to utilize the saline and waterlogged resources which otherwise remain abandoned. The main focus of this intervention is the remediation of saline wastelands through cultivation of biomass species for energy production, biomaterials and fodder and on the tree component of agroforestry systems (Singh and Dagar 1998). For example, in saline areas, trees and salt-tolerant plants can be an alternative to conventional agriculture. Trees on saline wastelands produce timber for construction or for energy, i.e. charcoal for cooking or electricity production through gasifiers. They also function as windscreens, protect the soil against erosion, add organic matter and nitrogen in soil, help in breaking hard pans in alkali soils and above all sequester carbon helping in mitigating climate change. A separate chapter has been included in this volume on agroforestry potentials on saline environments; therefore, that aspect is not included here to avoid repetition.

Two desert halophyte plants, *Tamarix* spp. and *Euphorbia tirucalli*, constitute good source of biomass under extreme desert conditions (Eshel et al. 2011). *Tamarix aphylla/articulata* (erect type) trees produced 52 and 26 Mg ha^{-1} organic biomass when irrigated with reclaimed sewage (EC approx. 3 dS m^{-1}) or brine (EC approx. 7–10 dS m^{-1}), respectively. *Euphorbia tirucalli*, a desert succulent, was suggested as a potential biofuel crop by Nobel laureate Melvin Calvin (Nielsen et al. 1997). In recent experiments, it exhibited a 60-fold weight increase 18 months after transplanting, when irrigated with saline sewage (EC 8–10 dS m^{-1}), generating a crop rich in carbon and hydrogen that has potential for being directly converted into biofuel (Eshel et al. 2010). Studies by Ravindran et al. (2007) on the reclamation potential of halophytic herbs such as *Suaeda maritima*, *Sesuvium portulacastrum*, *Clerodendrum inerme*, *Ipomoea pes-caprae*, *Heliotropium curassavicum* and one tree species *Excoecaria agallocha* on the northeast coast of Tamil Nadu, India, indicated the potentials of halophytes in restoring or utilizing the degraded salty soils. For more details on agroforestry of salt-affected and waterlogged inland and coastal soils and utilization of poor-quality waters for saline agroforestry, please see Dagar (2014, 2018), Dagar et al. (2014) and Dagar and Minhas (2016).

16.5 Domestication and Improvement of Salt Tolerance in Halophytes

The domestication of halophytes has been proposed as a strategy to expand cultivation of unfavourable salty lands. However, halophytes mainly have been considered for their performance in extremely saline environments, and only a few species have been characterized in terms of their tolerance and physiological responses to moderately high levels of salinity. Halophyte domestication and improved crop salt tolerance have yet to be given a high priority due to the fact that salinity is still perceived as a localized constraint rather than a regional or global stress on agricultural production. As an alternative to improving the salt tolerance of plants that already have desirable commercial traits, the domestication of halophytes is focused on improving the agronomic characteristics of wild salt-tolerant species through selection and breeding. By far, the most critical feature of successful halophyte domestication is the infusion of private and public capital for germplasm collection, breeding programs and biosaline applications in the field. As discussed earlier, in recent past several underexplored and most potential halophytic species both woody and herbaceous perennials as well as annuals have been evaluated for their salt tolerance limits, and successful species are identified for different situations and agroclimatic regions, which may be domesticated successfully for getting high income for different stake holders. Many of these can serve as food, forage and medicine and also for landscape development. The future of saline agriculture/ agroforestry is quite bright and in the future, it will help in not only increasing productivity but also solving the climate-related problems.

16.6 The Way Forward

The continuous expansion of salt-affected land (both in coastal and inland areas) is highest in the most populated and economically challenged countries such as India and is posing a serious threat to sustainable agricultural production. Halophytes, in such a scenario, may provide opportunities for cultivation of fodder and energy crops using saltwater for irrigation. This is a hugely exciting prospect given the current and projected world shortages in freshwater but remains a relatively unexplored research area.

Collection and preservation of seed and germplasm are perhaps the most immediate priorities before halophytes can be bred for commercial and environmental purposes. The availability of seed and germplasm for research, breeding and experimentation must be secured by both public and private institutions as an extended gene pool will prove invaluable for future domestication. Due to the myriad of factors influencing plant response to salinity, attention should be given to the identification and collection of genotype or population variations among the most promising species. Germplasm collection and preservation must be given precedence until the economic value of halophytes is fully recognized, markets are established and commercial seed companies begin to take over this function.

There is a need for long-term experiments proving the sustainability of halophyte crop production and their economic prospective for future growers. Halophytic crops can make use of coastal saline soils and saline irrigation water, both of which are impediments for conventional crop production. However, to ensure lasting sustainability of saline agriculture, the correct choice of adequate cultivation systems is of utmost importance.

Sandy soils existing in coastal areas may be readily available for large-scale halophyte production without the risk of salt contamination occurring on fertile soils through Ca^{2+}/Na^{+} exchange and subsequent clay dispersion. Similarly, groundwater contamination should be avoided or adequate drainage needs be provided. Alternatively, protected agriculture in closed cultivation systems with hydroponics, constructed wetlands and artificial growth media may provide viable alternatives. Bioengineering techniques, more efficient enzymes and microbes could be designed to convert halophyte biomass into bioethanol and biodiesel in order to supplement fuel requirements of burgeoning population.

Availability of huge quantities of saline water highlights the importance of halophytes as a source of renewable energy, particularly since they do not compete with glycophytic food crops. There are still difficulties that should be overcome, such as direct germination in saline conditions or genotype selection. However, more and more research efforts are directed not only towards determining salt tolerance of halophytes but also towards the improvement of agricultural traits for long-term progress (yield, palatability, chemical composition and mechanical harvesting), testing market potential and finally securing farmers' income.

16.7 Conclusions

Salinity problems of soil and irrigation water have become detrimental in crop production in arid and semi-arid regions of the world. The problems are compounded in coastal areas which are subjected to frequent inundation of seawater and areas just away from coast due to seawater ingress resulting from continued abstraction of groundwater. Availability of huge quantities of saline water highlights the importance of halophytes as a source of renewable energy, particularly since they do not compete with glycophytic food crops. Cultivation of economic halophytes which are potential sources for food, fuel, fodder, medicines, etc. is of great value. Halophytes, in such a scenario, may provide opportunities for cultivation of food, fodder and energy crops using saltwater for irrigation. While some efforts made in this direction are encouraging, continued efforts are needed for managing these soils. Studies have shown economic halophytes like *Salvadora persica*, *Salicornia bigelovii*, *S. brachiata*, *Suaeda nudiflora*, *Cressa cretica* and *Atriplex nummularia* and many mangrove species hold promise in these areas that are good sources of edible and non-edible seed oils, protein, forage, greens, pulp for paper and ecorestoration of saline soils. Halophytic grasses and many forbs are good sources of fodder, due to their salt tolerance and salt compartmentation. This paper highlighted the economic halophytes that are ideal for coastal saline soils and also their efficacy in bioremediation, industrial application and healthcare and also suggested possible ways for its further improvement as agroforestry crops.

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Soil Microarthropods as Indicators of Soil Health of Tropical Home Gardens in Kerala, India

17

G. Lakshmi and Ammini Joseph

Abstract

Tropical home gardens are characterized by biodiversity making them beneficial agroforestry ecosystems. Home gardens associated with each dwelling provide direct benefits like food and fodder in addition to indirect benefits and ecosystem services like microclimate regulation and enhancement of the soil carbon content. The most important ecologically relevant fauna reported in home gardens is the soil microarthropods which are considered to be determinants of soil quality. Their features like edaphic adaptations which are helpful in participating in soil biogeochemical cycles through litter decomposition have made them important tools in assessing soil quality. Soil microarthropods being sensitive to soil temperature and soil moisture can alter in number and species composition in relation to seasonal perturbations and soil ecosystem alterations, thus functioning as an efficient tool in biomonitoring studies. The effect of temperature on soil microarthropods and common indices used in biomonitoring of tropical home gardens are discussed.

Keywords

Bioindicators · Home gardens · Soil health · Soil microarthropods · Soil quality · Soil temperature

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17.1 Introduction

Home gardens are considered to be valuable traditional agro-biodiversity systems (Kumar et al. 1994; Sankar and Chandrashekara 2002; Soumya et al. 2007) in the tropical regions, as they along with livelihood security provide ecosystem services like efficient nutrient cycling, low use of external inputs, and soil conservation (Torquebiau 1992; Jensen 1993a, b; Jose and Shanmugaratnam 1993) in addition to regulation of microclimate of the corresponding areas where they are present. About 15–20% of the world's food supply is provided by traditional multiple cropping systems including home gardens (Altieri 1999). They also contribute to enhancing food security of a nation (Mellisse et al. 2018). The home gardens are small-holder agroforestry systems with high tree densities and are ecologically significant ecosystems with high carbon stocks (Nero et al. 2018; Subba et al. 2018). It is reported that these traditional agroforestry systems in the tropics hold a number of annual and perennial plant species per field and most species have their economic importance as construction materials, firewood, medicine, food, and livestock feed. These trees also protect soil nutrients by reducing soil erosion. Another important contribution of tropical home gardens to soil biodiversity is by maintaining a population of soil microarthropods which are prominent players in soil organic matter recycling, thereby contributing to soil quality enhancement (Vreeken-Buijs et al. 1998). The active involvement of soil microarthropods in soil food webs helps in maintaining a healthy soil ecosystem. A recent approach to evaluation of the soil quality of home gardens is by utilizing the indicator value of soil microarthropods (van Straleen and Verhoef 1997) which has been used to estimate the soil quality (Paolo et al. 2010; Madej and Kozub 2014) in different land areas and has proved to be efficient. According to Giller (1996), soil communities help to sustain high biodiversity, but due to the lack of knowledge in the community structure and presence of gaps in description of the soil community species, they are called "the poor man's tropical rainforests" (Usher et al. 1979).

17.2 General Features of the Home Gardens in Kerala

The home garden generally represents an ecosystem with mixed plant functional groups like grasses, forbs, shrubs, trees, and climbers. The plant groups found in tropical home garden agro-ecosystems have economic significance in terms of their use as medicinal, flowering, and fruiting plants. The good canopy cover offered by trees and the extensive taproot systems help in reducing the overall temperature of the home gardens, reduce soil erosion, and maintain the groundwater table. The home gardens generally show horizontal and vertical stratification. In most home gardens in Kerala, vertical stratification is evident with grasses, herbs, shrubs, and trees. A study related to soil microarthropods was undertaken in rural home gardens in Kerala, India (Lakshmi and Joseph 2017). The home gardens in rural areas like Chengamanad generally have four strata with a height ranging from 70 cm to 28 m

Fig. 17.1 A rural home garden in Kerala without much intensive soil management

(Fig. 17.1), while home gardens in other urban areas generally represent less floral diversity and soil faunal composition.

The diversity of soil microarthropods in the home gardens is an important issue to be addressed considering its importance in soil health of home gardens which are the most important agro-ecosystems linked to livelihood security in coastal areas. This study addresses the soil microarthropods in home gardens in the light of a study undertaken in a rural area in Kerala, India, along with the findings from published research papers on soil microarthropods.

17.3 Diversity of Soil Microarthropods in Tropical Home Gardens

Soil microarthropods are edaphic fauna inhabiting soil and organic debris layer above the soil. Soil microarthropods, considered as "resource biota" contributing to litter decomposition, are important biodiversity component in the tropical home gardens (Fig. 17.2). The arthropod populations under different soil conditions were studied long back by Ford (1937) and later by Dhillon and Gibson (1962). From various studies, it has been understood that soil microarthropods are most abundant near the soil surface characterized by favorable moisture, aeration, and organic

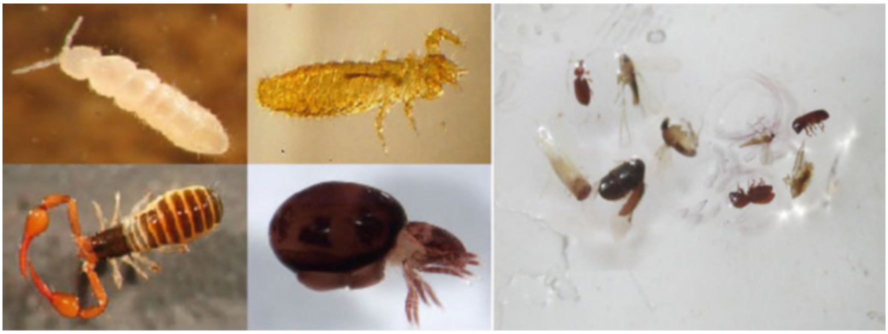

Fig. 17.2 Microscopic images of soil microarthropods (Source: Wikipedia) (clockwise: Collembola, Protura, Acari, Pseudoscorpionida). The second image shows a few preserved soil microarthropods found in the home garden ecosystems as observed under a camera (the image is magnified to understand the features)

matter content (Murphy 1953). The soil microarthropod composition also varies in accordance with soil depth. According to Price and Benham (1977), most arthropod groups declined rapidly in abundance with increasing soil depth. It is also found that the species composition and abundance of soil microarthropods are influenced by geographical location, physicochemical properties of soil, type of vegetation cover, as well as nature and depth of litter.

The attempts to correlate soil fauna with soil fertility date back to Soudek. Later, Fujikawa (1970) stressed on the role of soil microarthropods in litter decomposition and release of nutrients which has a positive effect on soil formation and soil fertility. The significance of Collembola and mites in the breakdown of organic matter and soil formation had also been pointed out by many (Fujikawa 1970; Wolters 2000; Eaton et al. 2004). Due to their widespread presence and abundance in tropical home garden agro-ecosystems, soil microarthropods can be used for the study of similar habitats with different management practices or different habitats within the same geographical area as the changes in the home gardens will be reflected as the presence, absence, or change in number of soil microarthropods. Soil microarthropods include Acarina, Collembola, Protura, Pauropoda, Diplura, and Symphyla groups (Lakshmi and Joseph 2017), among which Acarina and Collembola are found to be most abundant in home garden soils. The occurrence of soil microarthropods in soils is related to various factors such as temperature, moisture, organic matter, etc. For example, in a study of home gardens in a rural area (Lakshmi and Joseph 2017), microarthropod abundance was found to be higher during monsoon compared to summer (Fig. 17.3). Such regional studies point out that the various factors influencing microarthropod population in home gardens need a thorough study. Some of these are discussed here.

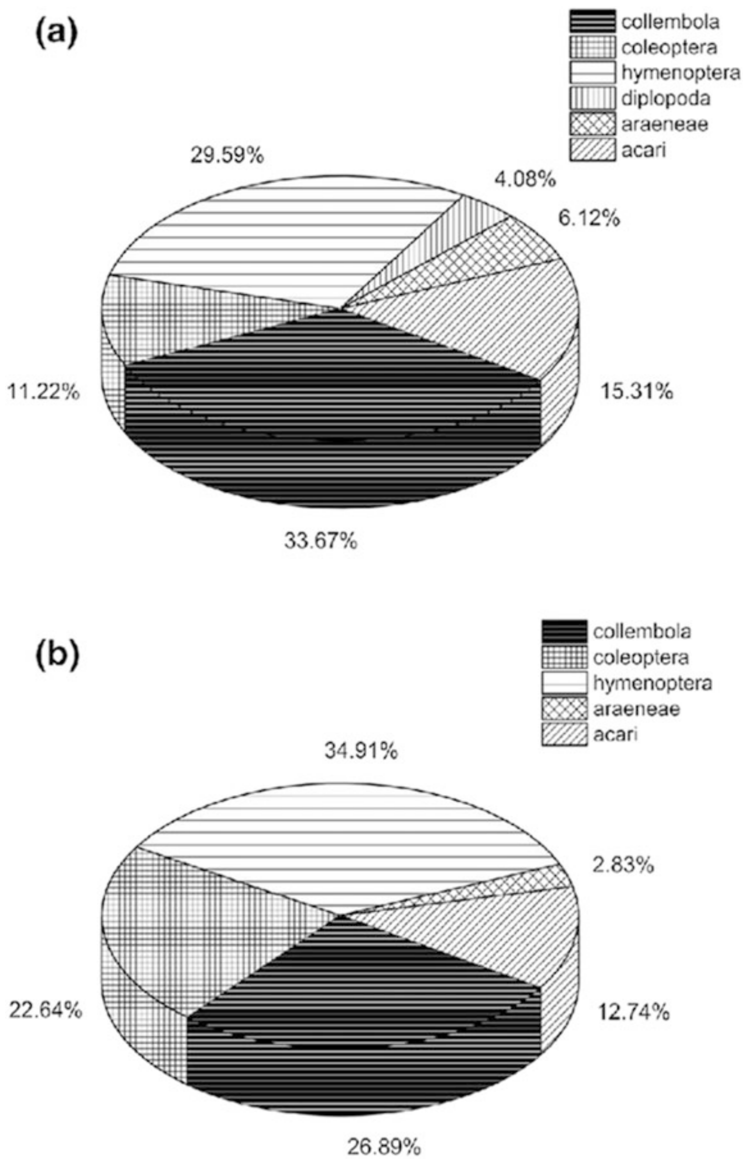

Fig. 17.3 Distribution of soil microarthropods during summer season (**a**) and monsoon season (**b**) in home garden of a village in Kerala, India (Lakshmi and Joseph 2017)

17.3.1 Effect of Soil Temperature on Soil Microarthropods

Temperature is one of the determining factors for the survival of soil microarthropods. Studies have proved that soil microarthropods can survive only in soils with optimum temperature which favors their physiological activities. Excess temperature will lead to heat stress in the organisms which responds to the increasing temperature in the form of movement to other soil ecosystems with more favorable conditions. The inability to tolerate increased temperature will ultimately lead to the death of soil microarthropods. Most Collembola and Oribatida mites have been reported to have their lethal temperature limits between 35 °C and 40 °C (Madge 1965; Hodkinson et al. 1996). Vannier (1994) presented a thermo-biological scale for insects, in which he suggested that the optimum temperature for the survival of insects is just above 20 °C. But certain studies have found that a temperature less than even 40 °C can be lethal to soil microarthropods (Malmstrom 2008). This normally occurs during events like forest fires. As sunlight plays an important role in maintaining the soil temperature of home gardens and direct sunlight is a limiting factor for soil microarthropod survival, it has been found that the soils which do not receive direct sunlight show a higher abundance of soil microarthropods compared to those which receive direct sunlight. This has been particularly noted in forest soils with a high canopy cover acting as a barrier for direct sunlight from entering the soil. The same principle is applicable for home gardens with thick canopy cover. Sunlight has a negative relationship with soil moisture, as direct sunlight will cause the evaporation of soil water leading to soil moisture deficit. The reduction in soil moisture will prompt the soil microarthropods to shift their niches to more favorable areas with good soil moisture content. Reduction in soil water content can also cause increased soil temperature leading to heat stress in soil microarthropods. Another observation to be noted is that in the regions where heat-absorbing black humus layer is exposed to direct sunlight, soil microarthropods can be subjected to mortality resulting from the elevated temperature (Malmstrom 2008). It is true that the thermal buffering of soil protects itself from changes in atmospheric temperature (Whitford 1992), and as we go deeper into the soil, the temperature variation decreases with depth to some extent. The saturation of soil with soil water can also reduce the threat of desiccation (Ghilarov 1977) caused due to increased temperature on soil microarthropods. But those soil microarthropods which survive above the soil are more prone to desiccation and death due to heat stress, while the soil microarthropod species that live on the litter surface have the ability to tolerate higher temperatures than species living further down in the soil.

17.3.1.1 Temperature and Seasonal Distribution of Soil Microarthropods

Soil temperature shows considerable variations in different seasons, especially in tropical countries which experience summer and rainy seasons. Hence the population of soil microarthropods also varies in tropical regions (Parwez and Abbas 2012). Studies have reported a high population of soil microarthropods during monsoon/wet months than during dry months (Verma and Yadav 2014; Begum et al. 2014; Lakshmi and Joseph 2017) in tropical regions. It is also reported that water is the most important factor influencing the population size of soil microarthropods (Badejo 1990). A study on Acari population by Badejo (1990) gives the finding that soil moisture content has a positive relationship with the population of Acari. Generally, a high abundance in soil microarthropods is noticed during wet seasons due to favorable conditions like increased soil moisture content due to precipitation and reduced evaporation. The increased soil moisture content during wet seasons can support a good population of soil microarthropods provided there is sufficient organic matter or litter content in the soil. During dry months, the soil conditions become reversed due to reduced soil moisture content as a result of increased evaporation and reduced precipitation. This can have a negative effect on the survival and physiology of soil microarthropods resulting in reduction of their numbers. For the survival of soil microarthropods, it has been found that a range of species-specific intermediate temperatures is found to be more suitable (Wallwork 1970) than a common range of temperature.

17.3.1.2 Effect of Fire on Survival of Soil Microarthropods

Forest fires are found to reduce the number of soil microarthropods. Since the temperature of the tropical regions is found to be increasing during summer, it can cause fire in home gardens as well. Fire can also occur due to burning of materials like waste during cleaning of households which the home gardens belong to. Fire releases enormous amount of energy, which increases the soil temperature. For understanding the effect of forest fires on soil microarthropods, a laboratory study was done, and it has been found that the determining factors for increased soil temperature during a fire are the rate of the burn, amount and quality of fuel consumed, soil moisture, and soil conductivity (Fisher and Binkley 2012). Rapidly advancing fires that consume little fuel have minor effects on soil temperature, while slower fires that consume more fuel may result in temperatures exceeding 70 °C at the soil surface, which decline to normal levels only at 15–30 cm depths (DeBano et al. 1998). This can be deteriorative to the majority of soil microarthropods living in the upper soil layers (Hagvar 1983), in addition to bottom-dwelling species of soil microarthropods. After a fire, it will take time for the soil microarthropod community to re-establish through secondary succession.

17.3.2 Effect of Canopy Cover on the Survival of Soil Microarthropods

Canopy cover in the home gardens indirectly affects soil microarthropod survival by increasing soil moisture content and reducing soil evaporation, thereby providing favorable microhabitat conditions (Lakshmi and Joseph 2015). The canopy cover acts as a barrier preventing direct sunlight from reaching the soil which reduces excessive heating of the soil and loss of soil moisture due to evaporation and increased soil temperature. The water drops on the leaves formed due to precipitation also fall down into the soil, adding to soil moisture content. Usually, a home garden with thick canopy cover offers a cool habitat for soil microarthropods throughout the year compared to with little canopy cover. The canopy cover also holds a good litter layer on the soil, which is invaded by soil microarthropods, helping in their degradation, thereby enhancing soil fertility. Reduced canopy cover often results in higher daytime temperature and in turn leads to reduced soil moisture and higher moisture loss from litter (Zhang and Zak 1995) ultimately resulting in unfavorable soil microarthropod habitats, reduction in microarthropod number, and thereby reduced rate of decomposition.

17.3.3 Climate Change and Soil Microarthropods

Warming and changes in precipitation can directly alter soil temperature and moisture, thereby affecting soil microarthropod reproduction and development rates (Uvarov 2003) in the home gardens. The impact of warming on soil microarthropods has been studied using different experiments (Coulson et al. 1996; Huhta and Hanninen 2001). According to Sjursen and Michelsen (2005), warming may affect soil microarthropod communities by changing the abundance and composition of soil organisms which they depend for food. Elevated temperature can also affect soil microarthropod communities by causing a change in plant physiology in the home gardens where they belong to. This happens during extreme summer where the soil becomes devoid of moisture causing water stress to the plants in home gardens. Due to reduced soil moisture content, the biomass from the trees falling on soil undergoes slow decomposition, reducing the litter content in the soil. Since the soil microarthropods are litter dwellers, the reduction in the litter content may affect their survival, ultimately resulting in reduction of their numbers. Kardol et al. (2011) has studied the effect of climate change on soil microarthropods using laboratory experiments. According to Harte and Rawa (1996), warming increased microarthropod abundance and biomass under wet conditions compared to dry conditions. This may be because the soil moisture present during wet conditions offers a favorable environment for the survival of soil microarthropods, while the reduced moisture content during dry seasons causes a threat to their survival.

17.4 Soil Microarthropods and Soil Health

The concept of "soil health" refers to a soil ecosystem which can support the existence and growth of plants and soil organisms like soil microbes and other edaphic fauna like soil invertebrates and vertebrates. While the layman's concept of soil health refers to a soil rich in nutrients which are helpful for the survival of plants, in scientific terms, soil health is a broader concept which includes all the organisms which are directly or indirectly affected by soil. This network includes organisms which have direct contact with the soil as well as those who indirectly depend on the benefits from the soil. According to FAO, "Soil health is the capacity of soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production." This definition can be extended in an environmental perspective as follows: A healthy soil is one that does not pollute the environment and contributes to buffer climate change by maintaining/increasing the carbon content.

Soil microarthropods being inhabitants of soil can provide excellent information regarding soil health of tropical home gardens. Among the soil microarthropods reported, the commonly used indicators for soil health are Collembola and Acari. According to recent findings, soil quality of home gardens can be quantified using the bioindication value of soil microarthropods through different indices. The different steps involved in determining soil quality indices are soil sampling, soil microarthropod extraction, microarthropod specimen preservation, determination of biological forms, and calculation of indices (Parisi 2001; Madej et al. 2011).

17.4.1 Ecomorphological Index (EMI)

The ecomorphological index (EMI) is an index of soil quality given to the soil microarthropods, based on the morphotype of each organism. EMI values ranging from 1 to 20 are assigned to the soil microarthropods considering the morphological features like body length and edaphic adaptations like the absence of wings and visual apparatus. The EMI score uses the presence of eu-edaphic soil microarthropod as the criterion for estimating soil quality (Yan et al. 2012), rather than their abundance. A higher EMI value refers to a higher level of adaptation of soil microarthropods. Since eu-edaphic soil microarthropods are highly adapted to soil habitat, they usually have an EMI score closer to 20 compared to the epi-edaphic and hemi-edaphic organisms having a score closer to 1 (Parisi et al. 2005). Whenever two ecomorphological forms are present in the same group, the final score is determined by the higher EMI. In other words, the most highly adapted microarthropods belonging to a group determine the overall EMI score for that group. The EMI scores of various soil microarthropod groups are given in Table 17.1 (Parisi 2001).

17.4.2 QBS (Qualità Biologica del Suolo) Score

QBS index ("Qualità Biologica del Suolo") or Biological Quality of Soil proposed by Parisi (2001) is based on the concept that the higher the soil quality, the higher the number of soil microarthropod groups adapted to soil habitat. The QBS index is calculated as the sum of EMI values in each soil (Parisi 2001). Two types of QBS index are reported, namely, QBS-ar and QBS-c. While QBS-ar relies on the soil quality index determination using soil microarthropod fauna present in a given area obtained by adding up the EMI scores, QBS-c is based on the Collembola-Acari ratio. For estimation of QBS-c, the Collembolans are separated into six groups, namely Podurid, Onychiurid, Isotomid, Entomobryid, Neelid, and Sminthurid. The biological form with the higher EMI value is recorded, and the EMI scores are

Table 17.1 EMI scores of soil microarthropod groups (Parisi 2001)

Microarthropod group	EMI score
Protura	20
Diplura	20
Collembola	1–20
Microcoryphia	10
Zygentoma	10
Dermaptera	1
Orthoptera	1–20
Embioptera	10
Blattaria	5
Psocoptera	1
Hemiptera	1–10
Thysanoptera	1
Coleoptera	1–20
Hymenoptera	1–5
Diptera (larvae)	10
Other holometabolous insects (larvae)	10
Other holometabolous insects (adults)	1
Acari	20
Araneae	1–5
Opiliones	10
Palpigradi	20
Pseudoscorpiones	20
Isopoda	10
Chilopoda	10–20
Diplopoda	10–20
Pauropoda	20
Symphyla	20

Table 17.2 Soil quality classes based on QBS scores (Parisi 2001)

Criterion	QBS score	Soil quality class value
Only epi-edaphic groups present (eu-edaphic groups absent)	–	0
Only hemi-edaphic groups present (eu-edaphic groups absent)	–	1
Proturans and Onychiurids absent	≤ 50	2
Proturans absent and Onychiurids present	>50	3
Proturans present	≤ 100	4
Proturans present and QBS $>$ 100	≤ 200	5
Proturans present	>200	6

summed to get QBS-c index. According to Parisi (2001), based on the QBS score, seven soil quality classes can be identified in a home garden (Table 17.2).

The EMI and QBS scores can be effectively used as scores for assessing the soil health of the tropical home gardens due to two reasons: (1) soil health is dependent on soil temperature and associated factors like soil moisture content and soil organic carbon and (2) the higher the soil temperature, the lower will be the QBS and EMI scores. The relation of soil quality indices with soil health was studied in different home gardens. Since tropical countries have a climate that is variable, showing gradation of temperatures and soil moisture and organic carbon content, the soil quality indices will act as a measurement of soil quality because the soil microarthropod fauna also change under the influence of soil temperature and thereby the associated factors like soil organic carbon and soil moisture content.

A simple representation regarding the effect of soil temperature on soil quality of home gardens is shown in Fig. 17.4.

Apart from soil temperature, soil moisture content and soil organic matter content also determine the QBS and EMI scores. Since all of these are dependent, it can be concluded that a change in any one of these will affect the soil microarthropod population and thereby the QBS score. The formation of organic matter in soil is favored by increased soil moisture content and increased amount of litterfall. The increased litterfall in the tropical home gardens can support a high number of

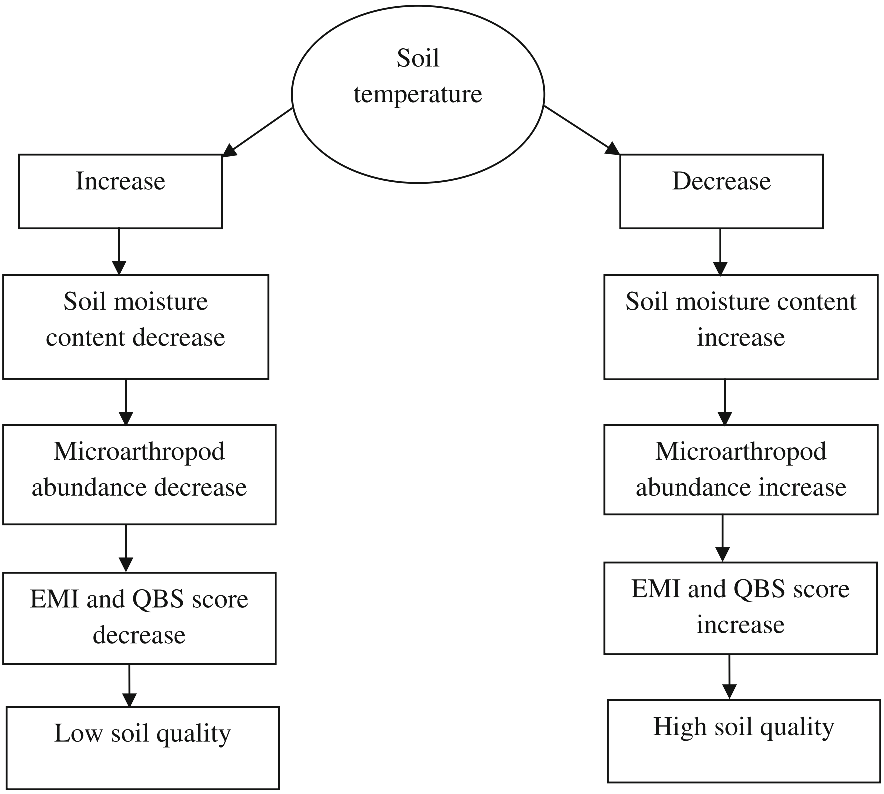

Fig. 17.4 Relationship among soil temperature, soil moisture, and soil health of tropical home gardens

eu-edaphic soil microarthropod fauna which will in turn increase the QBS value of the home garden soils. Since an increased QBS-ar value is a determinant of higher soil quality, the home gardens with higher QBS-ar scores are the ones with better soil quality. As management practices like cleaning the home gardens remove the litter cover from the soil, the soil quality of well-managed home gardens is found to be less when compared to the unmanaged home gardens (Gope and Ray 2006; Lakshmi and Joseph 2017). Hence unmanaged tropical home gardens with good canopy cover are a very good storehouse of soil microarthropods which can enhance the soil quality compared to intensively managed home gardens with domesticated plants.

17.5 Conclusion

Soil microarthropods, the determinants of soil quality of tropical home gardens, are affected by change in soil temperature, soil moisture, soil organic carbon, and anthropogenic activities like land management practices. The relationship of soil microarthropods to soil temperature can be utilized for the assessment of soil quality of tropical home gardens with the help of soil quality indices, and this can serve as a good support for the implementation of proper management practices of tropical home gardens in the future. This approach will also help in developing a common database regarding the soil quality of home gardens in the tropical regions and its changes in the future.

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