Jagdish Chander Dagar
Vindhya Prasad Tewari *Editors*

Agroforestry

Anecdotal to Modern Science

Springer

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Foreword

In the past, urban expansion has been at the expense of forests and woodlands. The accumulated effects of these changes are reflected in serious soil degradation, desertification and loss of biodiversity, leading to environmental insecurity and vagaries of climate change. Integrating trees on agricultural fields is one of the solutions for addressing these challenges. Agroforestry has the potential to restore degraded ecosystems and render environmental services along with socio-economic benefits.

In recent years agroforestry has been developed as an autonomous science that aims at helping farmers to increase the productivity, profitability and sustainability of their land, and, hence, scientific efforts have been made to classify, understand and improve models empirically established over the centuries by farmers' wisdom. Agroforestry imparts methods of ameliorating and mitigating the effects of harsh and erratic climatic conditions and poor soils, raising soil fertility buildup and enhancing symbiotic activities that help crop growth and sustainable production of food and feed, fuel, timber, fibre, medicines and several other products of day-to-day utilization on farms.

The need for sound scientific information in the development of agroforestry technologies at various levels has grown significantly in recent years. Against this background, this book *Agroforestry: Anecdotal to Modern Science*, edited by Dr. J.C. Dagar and Dr. V.P. Tewari, which encompasses 35 chapters contributed by leading agroforestry researchers from various countries throughout the world, is a very welcome move and will be extremely useful to everybody in understanding the evolution of agroforestry from a traditional system to modern art and science.

The editors of this book have embarked on a wide range of topics dealing with the evolution of agroforestry, traditional agroforestry systems, agroforestry as a modern science, the monitoring and assessment of trees outside forests, new approaches in cut-and-carry systems, urban and peri-urban agroforestry, the role of microbial biodiversity and soil micro-arthropods in enhancing agroforestry production, the regulation of ecosystem services delivered by agroforestry in different parts of the world and agroforestry for climate change mitigation.

I sincerely hope that this book will serve as a useful text of reference for researchers and students engaged in the pursuit of agroforestry research and development and will be a useful tool for those who are involved in policy issues. I congratulate the editors of this book for their sincere efforts.

Chennai, India M. S. Swaminathan

Preface

Most of the world's closed forests, covering approximately 2800 million hectares, are found in the Northern Hemisphere and in the equatorial region. The pressures exerted by the rising human populations on uninhabited forest areas are a cause of great concern. Natural forests are being destroyed permanently at a rate of 8–10 million hectares per year in the tropics. Appropriate and effective technologies have to be developed for the sustainable management of the forests and plantations. Trees outside forests play a very important role in catering to the day-to-day need of the rural population, and hence assessment of this valuable resource based on the reliable data is the need of the hour. Suitable strategies must be developed for the genetic improvement of the tree species for enhancing production to meet the needs of increasing populations. In recent times, agroforestry is playing a very important role in revegetating the degraded lands across the globe. Many of the anecdotal agroforestry practices, which are time-tested and evolved through traditional indigenous knowledge, are still being followed in different agro-ecological zones with some modifications. 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, alley cropping, and park systems have evolved as modern agroforestry systems.

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. Research efforts have shown that most of the degraded areas including saline, waterlogged, and perturbed ecologies like mine spoils and coastal degraded mangrove areas can be made productive by adopting suitable agroforestry techniques involving highly remunerative components such as plantation-based farming systems, high-value medicinal and aromatic plants, livestock, poultry, forest and fruit trees, and vegetables. New concepts such as integrated farming systems 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.

It is both a challenge and an opportunity to the scientific community working in this interdisciplinary field. To prepare themselves better for facing future challenges and seizing the opportunities, scientists need access to synthesized information and develop technologies to assess the environmental benefits we get from different agroforestry services. The global community is still only in the beginning phase to recognize the potential benefits of many underexploited systems to address the most intractable land management problems of the twenty-first century, such as food and nutrient security, climate change mitigation and adaptation, biodiversity conservation, and rehabilitation of degraded ecosystems. As we move forward to vigorously exploit these potential benefits, we will witness the involvement of agroforestry and its progress for solving these problems and be able to ensure food and environmental security at a global level.

To develop the strategies for moving forward, it is essential to evaluate the past and present status of research and concepts and think of developing strategies for further progress in the field seeing the modern challenges ahead. Therefore, it has been tried to obtain contributions from eminent persons working in their fields of specialization at a global level. Many of the articles are related to the most modern fields of agroforestry such as rehabilitation of problem soils; urban and peri-urban agroforestry; mitigation of climate change through carbon sequestration; role of pollinators, arthropods, and microbiology in enhancing agroforestry production; and environmental services availed from different agroforestry systems. The editors are thankful to the contributors as well as to all those who helped in the preparation of this volume. We hope that this compilation will be of value to the researchers and students pursuing the goals of harnessing management and genetic options to enhance farm productivity and value of trees and medicinal plants to provide our populace with forest produce of day-to-day need on a sustained basis and improved environmental quality for better health, thought, and mind. The book will also be useful for teachers, researchers, students, and policy makers and all those who are interested in this unique field of agroforestry.

New Delhi, India Jagdish Chander Dagar
Shimla, Himachal Pradesh, India Vindhya Prasad Tewari

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About the Authors

Dr. Jagdish Chander Dagar has published more than 280 research papers in peer-reviewed journals and papers in proceedings of conferences/symposia, has authored and edited 12 books, and has written more than 50 articles. He was the Assistant Director General at the headquarters of ICAR and Emeritus Scientist. His research interests are in the areas of biosaline agriculture, agroforestry, management of natural resources, rehabilitation of degraded lands, biodrainage, ethnobotany, plant ecology, climate change, and sustainable agriculture and policy. In recognition of his research contributions, Dr Dagar has been conferred with several awards and honors: the Sajjad Memorial Gold Medal, the ICAR's Hari Om Ashram Trust Award, UGC's Swami Pranavananda Saraswati National Award, CSSRI Excellence Award on Soil Salinity and Water Management, Bharat Excellence Award and Gold Medal, and Dr KG Tejwani Award for Excellence in Agroforestry Research and Development. Further, he is a Fellow of the National Academy of Agricultural Sciences and Fellow and Life Member of several other professional societies. He is Chief Editor of the journal *Soil Salinity and Water Quality*.

Dr. V.P. Tewari is a Scientist at the Indian Council of Forestry Research and Education (ICFRE), Dehradun (an autonomous council under the Ministry of Environment & Forests, Government of India) and is presently working as Director of the Himalayan Forest Research Institute, Shimla. He also worked as an FAO fellow for 1 year (1995 to 1996) at the Institute of Forest Management and Yield Science, University of Goettingen (Germany). He was awarded the Brandis Prize in 1998 by the Indian Forester for publishing the most outstanding paper in the field of silviculture and forest management. He has authored over 70 research papers in various peer-reviewed international journals and has 3 edited books to his credit. He has also presented 38 papers at various international and national conferences and workshops. Lastly, he has served as a National Subject Matter Coordinator on "Forest Biometrics" at the ICFRE and is listed in the UNCCD Roster of Experts from India.

Chapter 1
Introduction

Vindhya P. Tewari and Jagdish C. Dagar

Abstract Agroforestry, based on ecological principles, is of paramount importance in the areas where crop production is very insecure due to variable and harsh climatic conditions. Besides providing food, fodder, fuel, timber and several other products of day-to-day use, agroforestry offers security to inhabitants and their animals during famines and droughts. Forestry with agriculture provides support to the farming system by way of conferring stability and generating assured income. Agroforestry can mitigate the impact and consequences of these environmental limiting factors. Time-honoured suitable agroforestry models are required, especially for the arid regions. Agroforestry, as subject of scientific investigation, assumes wider recognition in view of the need to maximise production 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 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. Research efforts have shown that most of the degraded areas including saline, waterlogged and perturbation ecologies like mine spoils and coastal degraded mangrove areas can be made productive by adopting suitable agroforestry techniques involving highly remunerative components such as plantation-based farming systems, high-value medicinal and aromatic plants, livestock, poultry, forest and fruit trees and vegetables. New concepts such as integrated farming systems, domestication of high-value native plants and urban and peri-urban agroforestry have emerged.

Keywords Agroforestry · Arid region · Model trees · Tree-crop models · Sustainable development · Integrated farming systems · Urban and peri-urban agroforestry

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1 Introduction

Agroforestry is as old as agriculture itself. 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 park systems have evolved as modern agroforestry systems.

In recent years, agroforestry has been developed as an autonomous science based on ecological principles (Batish et al. 2008) that aims at helping farmers to increase the productivity, profitability and sustainability of their land; hence scientific efforts have been made to classify, understand and improve agroforestry models empirically established over the centuries by farmers' wisdom. It is interesting to note that similar systems have indeed been independently built up in the arid lands of various continents.

Agroforestry practices are unique, and through their proper application, each objective of economy, conservation of resources and social acceptance can be met. Agroforestry practices are designed to fit specific niches within the farm to meet specific objectives. When properly designed, agroforestry practices can achieve a balance between diverse, and often seemingly opposed, objectives.

Agroforestry imparts ameliorating and mitigating effects of harsh and erratic climatic conditions and poor soils, raising soil fertility build-up and enhancing symbiotic activities that help crop growth and sustainable production of food and feed, fuel, timber, fibre, tools, draught power, medicines and several other products of day-to-day utilization on farms. In addition, it permits higher security and sustainability during droughts and famines that are not infrequent in dry regions.

Some important contributions of agroforestry are increased and more stable food production directly due to the introduction of trees (fodder and fruits) or indirectly through increased soil fertility resulting from the organic matter produced by deciduous tree organs, including rootlets. The agroforestry products and services provide several benefits such as higher incomes due to the sale of tree products; reduced external dependence on external sources for key agricultural inputs such as fertilizers and subsistence products, fuelwood and building material; and reduced grazing pressure on the rangelands and forest due to the contribution of the trees to the forage balance of the farms. Microclimatic mitigation and reduction of soil erosion and of the siltation of waterways, although less apparent and difficult to quantify on the short term, are very beneficial on the long-term stability and sustainability of these systems.

Agroforestry is not restricted to farmland but is also amenable to improve rangeland, wasteland, eroded areas and degraded land, as long as access control to people and stock is feasible. In the arid regions of Rajasthan state 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, rainwater is collected on an uncultivated catchment area and driven to a nearby lower farmed area where it is kept percolating through small banks. A similar system ("meskat") is used for maintaining arid land olive tree groves in Northern Africa.

Despite the many promises and benefits that agroforestry holds under appropriate conditions, there are also limitations arising from biophysical, socio-economic and socio-political conditions such as land ownership and control, usage rights and the like. One limitation comes from the time lag until the full benefits of agroforestry practice become apparent. Soil conservation benefits and cash from tree harvesting may only become apparent several years after the establishment of the system. These problems are partly similar to those encountered in forestry. They may be overcome by careful planning and appropriate combination of crops and animals with trees, both in space and time.

In recent years, agroforestry (AF) has gained considerable popularity as an approach to land use planning. Integrated land use with AF practices helps to increase both the quantity and quality of production, generates a sustained agricultural production base, provides ecological security and raises living standard of the practicing population through higher and sustained incomes simultaneously assuring availability of basic necessities of life. Farm households with a low level of external inputs may be managed on a sustainable basis by adopting agroforestry practices. The basic premise of an AF system is that the total net benefit is greater in multiple uses than the single production system (Tewari and Singh 2000).

2 Model Trees in Agroforestry

A model tree for agroforestry purposes should be characterized by a fast vertical growth, a small crown, few branches with a narrower angle, a loose canopy and a self-pruning habit, straight and clear bole with an aggressive apical dominance, a high proportion of main stem in the overall biomass and deep and deciduous roots. Fast-growing trees get quickly established, thus freed earlier from possible livestock damage, and have an earlier harvesting age. Trees with a small crown, having fewer and narrow-angled branches, exhibit a compact form. Such trees require little horizontal space hence a larger density. Consequently, returns per unit area are higher. A loose canopy permits light transmittal and less interference to the crop. Straight-growing trees occupy less horizontal space and thus interfere less with the growing crop. Straight and clear boles provide quality wood that, in addition, are easier to handle in processing (Bangarwa 1998). Root system in agroforestry trees must be deep. This is the more important in dryer areas where the moisture stress to the crops is common. Nitrogen-fixing trees should be preferred for their larger soil enrichment potential; they are also known for the high caloric value of their wood. Trees with shallow root systems as some *Acacia* spp. compete with crops for moisture and nutrients. It has been observed in the drier areas that the crops invariably fail because of *Acacia*, in the vicinity of these trees. Also, the shallow root system interferes in the usual agricultural operation like ploughing, sowing and hoeing of the annual crops. Thus, a deep root system is one of the major requirements of agroforestry trees.

The strategy can further boost the fuelwood production. The pressure on the land is increasing for the supply of wood, feed and biomass for fuel and energy. Vast areas in India and elsewhere are degraded wasteland not amenable to high-input commercial agriculture. In most of these drought-prone or saline-alkaline areas and other fragile environments where annual field crops cannot be grown, agroforestry species are the answer for sustainable development.

These days many fruit trees such as species of *Citrus*, *Emblica officinalis*, *Psidium guajava*, *Punica granatum*, *Ziziphus mauritiana*, *Achras zapota*, etc. are found to be preferred along with cereal crops. This is a good trend as through fruits the problem of nutritional security will be solved to some extent. This will also help in increasing the farm income. Nair and Dagar (1991) listed several multipurpose trees suitable for different agroclimatic regions.

3 Suitable Agroforestry Models

We have gone a long way to develop several agroforestry models for different agro-ecological situations and site-specific conditions such as reclaiming salty and water-logged soils, rehabilitation of ravine lands, restoration of mine spoil areas and restoration of degraded mangrove areas. Some of these have been discussed in this book in separate chapters.

3.1 For Arid Areas

(i) *Silvopastoral systems*: for maintaining ecological balance between human and livestock populations, it is necessary to use at least 20–25% of the cropland for silvopastoral activity. This is mostly needed for village common land. Tewari et al. (1999, 2014) have given interesting account of this practice in desert conditions.

(ii) *Horticultural-pastoral systems*: Fruit trees-based systems are very much important for nutritional and food security of common people. Species of *Ziziphus* are the most usable horticultural species for food, forage and fuel in the existing systems of the arid zone. The *Ziziphus mauritiana* (“ber”), or *Z. jujube* (“bordi”) grafted on *Z. nummularia* are preferable for fruit and forage yields, but preferred grass species vary with rainfall conditions and locations.

(iii) *Agro-silvo-horticultural systems*: the usable species is “ber”, as in the traditional way. From an investment of one rupee in these, the return is estimated to be ₹3.33–4.00.

3.2 For Semiarid and Humid Areas

Huge literature is available for different homegardens across the world (Kumar and Nair 2006), which are time tested and lifeline for small farmers in coastal and island regions. Many of these have been improved and researched for their sustainability. Recently, enough attention is being paid on integrated farming systems involving different components of agroforestry such as forest and fruit trees, plantation crops, cereal and pulse crops, medicinal and aromatic crops, fishery, poultry, duck rearing, piggery (e.g. north-eastern India), livestock, beekeeping, etc. depending upon the situation and requirement of the farmers. These have helped in sustaining the income, production and environment. Many farmers have gone for industrial plantations such as coffee, tea, cocoa, spices, oil palm and rubber in tropical regions and eucalyptus and poplar in Indo-Gangetic plains.

4 Role of Agroforestry for Sustainable Development

Studies undertaken on various aspect of agroforestry during the last many years have indicated the suitability, social and economic viability and environmental utility of various agroforestry models practiced in different regions. More recently, the role of agroforestry in rendering environmental services has been widely recognized (Nair et al. 2009; Nair 2012; Jose 2010; Nair and Garrity 2012; Dagar and Tewari 2016). In this contribution also, the role of micro-arthropods, entomology, pollinator services and regulating ecosystem services by agroforests has been included.

4.1 Increased Production and Enhanced Farmers' Income

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. Leaf litter also generally aids micronutrients in the soil. Combining agricultural crops with trees helps in increasing the productivity of the land. Higher yields of crops have been observed in forest-influenced soils than in soils not supporting forest (Chaturvedi 1981; Sanghal 1983; Verinumbe 1987; Tewari et al. 2014). Approximately 20% higher yields of grains and wood have been reported in agroforestry practice from Haryana and Western Uttar Pradesh than from pure agriculture (Dwiwedi and Sharma 1989).

Agroforestry gives more income to the farmer per unit area of land than pure 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 (Chaturvedi 1981; Lahiri 1983; Pillai 1983; Mathur and Sharma 1983; Mathur et al. 1984; Chandra 1986; Patel 1988; Tewari et al. 2014). It is now a recognized fact that agroforestry is more beneficial than sole crops, particularly in dry regions.

4.2 Supplement Food and Fodder

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 supplementing the nutrients in the form of fruits, green vegetables, fish, eggs and other livestock products. *Moringa* tree is found almost in each house in southern regions of India, which is one of the most nutrient-giving plants, rich in minerals, vitamins, iron and other contents. Small ruminants are almost solely dependent on tree fodder obtained from agroforests or trees outside forests.

4.3 Soil Improvement

Agroforestry systems protect soil from several adverse effects. 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 1987, 1993; Young 1989; Dagar et al. 2014). Tree crowns protect the soil from the impact of raindrops and create a specific microclimate in the particular area (Pradhan 1973; George 1978; Ghosh et al. 1980; Nair 1993). Frequent droughts and failure of crops are 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 large fluctuation in yield from year to year. Agroforestry can, therefore, provide economic viability in the years when rain fails. Several experiments have shown that agroforestry helps in reclamation of salt-affected soils (Dagar et al. 2001; Singh and Dagar 2005; Dagar 2014; Dagar and Minhas 2016).

4.4 Environmental Improvement

Windbreaks and shelterbelts are known to have beneficial effects on agricultural production throughout the world (Carborn 1957; Frank et al. 1976; Tewari et al. 2014). Increased agricultural production due to windbreaks and shelterbelts in India has also been reported (Bhimaya et al. 1958; Kaul 1959; Rao and Sita Ram 1980). It has been now well established that agroforestry renders environmental services through carbon sequestration, soil reclamation and biodiversity (including soil microbial) improvement. Jose (2010) has reviewed important work on the subject carried out across the world.

The penetration of radiant energy is one of the most important factors that influences the success of the pasture or crop establishment in an efficient agroforestry/silvopastoral system (Jackson and Palmer 1979). When insufficient light energy is available and photosynthesis is curtailed, the roots of the plants undergo a reduction in growth (Daubenmire 1974). A lot of progress has been made in root research in tropical agroforestry that contributes to better understanding of the interactions of roots and below-ground resource used in sequential and simultaneous systems (Akinnifesi et al. 1999). New tools have been developed that allow measurements of root growth and interactions in woody and herbaceous species associations. There is much increase in information on root architecture, root behaviour and functions of potential tree and shrub species grown in association with crops (Schroth et al. 2008). Root behaviour is influenced by genetic, site and management factors. The information can be utilized for minimizing competition for nutrients and moisture in agroforestry systems, especially under stress conditions, as often observed in dry zones or on acidic soils. Research is needed for more efficient utilization of below-ground growth resources by crops and/or woody species to optimize returns in various agroforestry systems.

5 Agroforestry as Problem-solving Science

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. Research efforts have shown that most of the degraded areas including saline, waterlogged and perturbation ecologies like mine spoils and coastal degraded mangrove areas can be made productive by adopting suitable agroforestry techniques involving highly remunerative components such as plantation-based farming systems, high-value medicinal and aromatic plants, livestock, poultry, forest and fruit trees and vegetables. 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 have been included in this publication.

6 Conclusions

Agroforestry is both an art and a science. There are many ways for trees to meet conservation, economic and societal goals, and we learn every day about effective technologies to ensure the use of agroforestry practices to meet one or more specific goals in a better way.

Agroforestry should be looked upon as a means for improving the socio-economic conditions of the rural poor and should be the main plank of integrated rural development programs. To increase fuel, timber and fodder production, agroforestry programs should be adopted in a large scale. 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. The main component of the production technology are proper tillage operation, appropriate lopping, appropriate grazing, appropriate 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.

The absence of an effective agroforestry policy in developing countries was identified by FAO (1977). This organization recognized that policy issues need to be addressed for an all-out development of agroforestry. Institutional issues are also critical and need attention. For a national-level planning of agroforestry to succeed, it will be necessary to develop effective means of co-ordination between different sectors and the development of a common understanding of policy and legal issues affecting the adoption of an agroforestry policy framework. The initiative for National Policy on Agroforestry in India was taken at the same time when FAO was preparing guidelines for decision-makers for advancing agroforestry on the policy agenda (FAO 2013). After long deliberations and discussion, India launched a forward-looking National Agroforestry Policy in 2014 (National AF Policy 2014). However, to implement the same, appropriate guidelines for production of quality planting material, supply system and coordination, convergence and synergy between various sectors linked with agroforestry will be required. This will require adequate research interventions and support as well as trained manpower.

In the whole world, only India has formulated agroforestry policy in 2014; however, to make it more effective, the following points may be considered to strengthen agroforestry policy framework (Kishwan 1996):

- Apportioning land for different land uses on national, regional and local levels
- Refining government regulations on movement, sale and trade of agroforestry products
- Defining the roles of public and private organizations, banks and NGOs
- Resolving conflicts between different land uses
- Developing on-farm condition research
- Generating sufficient and quality germplasm through accredited nurseries

- Strengthening extension networks and exchanges between user agencies
- Equitable distribution of benefits

Agroforestry should be looked upon as a means for improving the socio-economic conditions of the rural poor and should be the main plan of integrated rural development program. In order to increase fuel, timber and forage production, agroforestry programs should be adopted on a large scale; this would include rural woodlots for the rural areas (Singh et al. 1998).

Agroforestry programs should be implemented through forest department/agriculture department/forest research institutes/NGOs/village panchayats and extension agencies of the concerned departments. Programs should be time bound and target oriented. People's participation should also be ensured as it is a critical factor in the success of these programs.

It is both a challenge and an opportunity to scientific community working in this interdisciplinary field. To prepare themselves better for facing future challenges and seizing the opportunities, scientists need access to synthesized information and develop technologies to assess the environmental benefits we get from different agroforests. The global community is still only in the beginning phase to recognize the potential benefits of many underexploited systems to address the most intractable land management problems of the twenty-first century, such as food and nutrient security, climate change mitigation and adaptation, biodiversity conservation and rehabilitation of degraded ecosystems. As we move forward to vigorously exploit these potential benefits, we will witness the involvement of agroforestry and its progress for solving these problems and be able to ensure food and environmental security at global level.

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Chapter 2
Evolution of Agroforestry as a Modern Science

Jagdish C. Dagar and Vindhya P. Tewari

Abstract Agroforestry is as old as agriculture itself. 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 park systems have evolved as modern agroforestry systems. During past four decades, agroforestry has come of age and begun to attract the attention of the international scientific community, primarily as a means for sustaining agricultural productivity in marginal lands and solving the second-generation problems such as secondary salinization due to waterlogging and contamination of water resources due to the use of excess nitrogen fertilizers and pesticides. Research efforts have shown that most of the degraded areas including saline, waterlogged, and perturbation ecologies like mine spoils and coastal degraded mangrove areas can be made productive by adopting suitable agroforestry techniques involving highly remunerative components such as plantation-based farming systems, high-value medicinal and aromatic plants, livestock, fishery, poultry, forest and fruit trees, and vegetables. New concepts such as integrated farming systems 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. It is both a challenge and an opportunity to scientific community working in this interdisciplinary field. In order to prepare themselves better for facing future challenges and seizing the opportunities, scientists need access to synthesized information and develop technologies to assess the environmental benefits we get from different agroforestry services. The global community is still only in the beginning phase to recognize the

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potential benefits of many underexploited systems to address the most intractable land management problems of the twenty-first century, such as food and nutrient security, climate change mitigation and adaptation, biodiversity conservation, and rehabilitation of degraded ecosystems. As we move forward to vigorously exploit these potential benefits, we will witness the involvement of agroforestry and its progress for solving these problems and be able to ensure food and environmental security at global level.

Keywords Agroforestry · History · Concepts · Traditional AF systems · Improved AF systems · Wayforward

1 Introduction

Cultivation of trees and agricultural crops in intimate combination with one another is an ancient practice that farmers have used throughout the world, but agroforestry as a science has a recent origin. Agroforestry now has come of age during the past 35 years. During the earlier stages of this period, traditional practices involving numerous indigenous forms of trees and crops with and without animals were dominant and explained in emerging literature of agroforestry (Nair 1989, 1993; Singh et al. 1998; Dagar et al. 2014b; Dagar and Minhas 2016; Dagar and Tewari 2016a). Understanding the vast but mostly undocumented or partially documented indigenous knowledge concerning the traditional land management practices and land races and incorporating their underlying ecological principles in designing the improved systems and practices have been the key aspects during early stages particularly during 1980s and 1990s. Since then, numerous reports and compilations of improved agroforestry systems focused on specific ecological and geographical regions and individual countries as well as systems based on specific species or groups of species; and site-specific problem-solving systems have been produced from the tropical and temperate regions across the world (Tejwani 1994; Gordon and Newman 1997; Boffa 1999; Garrett et al. 2000; Elevitch 2007; Rigueiro-Rodriguez et al. 2008; Jose 2010; Nair and Garrity 2012a; Dagar et al. 2014b; Dagar and Minhas 2016; Dagar and Tewari 2016a; Peri et al. 2016). Today, agroforestry represents the modern, science-based approach to harness the sustainability attributes and production benefits of such time-tested practices, and its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use is receiving increasing attention in development programs including climate change around the world (Nair et al. 2016).

Most developments in agroforestry during last four decades of organized research have been based on “improved systems,” implying that they represent improvements and modifications of systems existed before. However, Nair et al. (2016) recently have shown the concern that over the years, the emphasis on the study of such indigenous agroforestry systems (AFS) has been sidelined or ignored.

According to them, the neglect of such systems has gone to the extent that sometimes discussions and descriptions of these systems are dismissed disparagingly. This has been referred as paradoxical, because one of the strong tenets of agroforestry and motivation for its promotion has been the importance attached to site-specific local knowledge surrounding the time-tested traditional systems. They have used term "*Cinderella*" to refer such "forgotten" or "downtrodden" AF systems. Actually, the word was popularized by Walt Disney Production's movie by that name expressing with a European folktale (Italian, *Cenerentola*; French, *Cendrillon* or *La Petite Pantoufle de verre*; German, *Aschenputtel*), embodying a myth element of unjust oppression. The word has, by analogy, become known to refer to an individual whose attributes were unrecognized or one who unexpectedly achieved recognition or success after a period of obscurity and neglect. Leakey and Newton (1994) earlier used the term *Cinderella species* to refer to the "really indigenous multipurpose trees, the products of which have traditionally been collected, gathered, and utilized by humans, and are still of enormous importance to many people around the tropics for food and nutritional security and welfare." Such location-specific, time-tested, indigenous systems that have been passed or ignored by "modern" agroforestry research have a lot to contribute to the development of improved agroforestry systems and practices (Nair et al. 2016).

The multitude of systems that have evolved over long periods in 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, fuel wood, 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 techniques. The prominent examples include multifunctional homegardens, which promote food security and diversity; fast-growing tree-based biodrainage plantations, which ensure lowering down of water table in waterlogged areas along with production of wood, food crops, and sequestration of carbon; woody perennial-based systems furthering employment generation and rural industrialization; domestication of local fruit trees ensuring food security and income generation through value addition; fertilizer trees and integrated tree-grass/crop production systems favoring resource conservation; tree-dominated habitats, which sustain agrobiodiversity; mangrove-based aquaculture sustaining livelihood, conserving biodiversity, protecting shoreline from natural disasters, and mitigating climate change; and urban and peri-urban agroforestry to make cities worth living, handling disposal of sewage water, and reducing air pollution. Thus, agroforestry has potential to meet challenges of the twenty-first century and beyond provided the policies of all governments are favorable for agroforestry developments. To understand transformation of agroforestry research development, we need to understand the agroforestry systems both anecdotal and improved ones along with their economic and socio-ecological principles. Some of these issues have been highlighted in this chapter in brief.

2 The History 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 man (*Homo sapiens*) learnt the art of domesticating plants and animals after leaving hunting and gathering habit. In about 700 BC, the hunting and food gathering system gradually gave way to food producing systems. The role of many common trees such as *khejri* or *samisami* (*Prosopis cineraria*), *aswattha* (*Ficus religiosa*), *palasa* (*Butea monosperma*), and *varana* (*Crataeva roxburghii*) in Indian folklife has been mentioned in ancient literature of *Rig Veda*, *Atharva Veda*, and other Indian scriptures (Mann and Saxena 1980). Horticulture, also as coexistent with agriculture, is found to have been prevalent from early historic period. Archaeological excavations corroborate early tree domestication around the settlements in South Asia. The evidence of this dates to the Mesolithic period (10,000–4000 BC) when fruits of 63 plants including *bael* (*Aegle marmelos*), gooseberry (*Emblica officinalis*), jujube (*Ziziphus mauritiana*), figs (*Ficus glomerata*), *mahua* (*Madhuca indica*), and mango (*Mangifera indica*) were reportedly consumed in one or the other form and were domesticated near the habitats (Randhawas 1980). Incidentally, some stray references occur in different texts of the *Vedic* literature in India and elsewhere (Raychaudhuri and Roy 1993; Pathak and Dagar 2000; Dagar and Tewari 2016b). For example, the cultivation of date palm (*Phoenix dactylifera*), banana (*Musa paradisiaca*), pomegranate (*Punica granatum*), coconut (*Cocos nucifera*), jujube, gooseberry, *bael*, lemon (*Citrus limon*), and many varieties of other fruit trees and requirement of livestock in agriculture and mixed economy of agriculture and cattle breeding may be traced in protohistory chalcolithic periods of civilization. Puri and Nair (2004) mentioned that rearing of silkworm (*Bombyx* spp) and lac insect (*Laccifer lacca*) was practiced in the Indian subcontinent during the Epic era of *Ramayana* and *Mahabharata* (7000 and 4000 BC, respectively).

Emperor Ashoka, a great Indian ruler (273–232 BC), encouraged a system of arbori-horticulture of banana, mango, jackfruit (*Artocarpus heterophyllus*), and grapes (*Vitis vinifera*). As per the second of the 14 *Rock Edicts of Ashoka* (257 BC), planting of medicinal herbs and trees besides shade trees along the roads and fruit plants on the wastelands was the accepted norms in those days – analogous to social forestry project of the present (Kumar et al. 2012). Further, the travelogue of Ibn Battuta (Persian traveler, 1325–1354 AD) provided the earliest literary evidence of intensively cultivated landscapes of Malabar Coast with coconut (*Cocos nucifera*)) along with black pepper (*Piper nigrum*) around the habitats (Randhawas 1980). Warriar (1995), while describing Wayanad as green paradise, mentioned that plough agriculture was prevalent in Wayanad in Western Ghats as early as in the Megalithic Age (between 400 BC and 400 AD), and spices like black pepper, ginger (*Zingiber officinalis*), and cardamom (*Elettaria cardamomum*) were often grown in association with woody perennials – as support or shade trees, since the early Middle Ages (500–1400 AD). The contents of *Krishi Gita*, over 300 years old book of agricultural verses in one of the Indian languages *Malayalam*, also reflect on the need to maintain tree cover on the land scape, plant fruit trees on cleared forests, gardens, and other leftover lands, avenue planting as well as leaving vestiges of forests in the midst of cultivated landscapes (Kumar 2008). Natural history studies during the two previous centuries (Mateer 1883; Logan 1906) also signify that the people in the southern parts of peninsular India, traditionally used their homesteads for a variety of needs such as food, energy, shelter, medicines, and other purposes. These evidences show that agroforestry was at the central stage in meeting the livelihood requirements in South Asia since ancient times.

Tracing the history of agroforestry, King (1987) stated that in Europe, until the Middle Ages, it was the general custom to clear-fell degraded forest, burn the slash, cultivate food crops for varying periods on the cleared area, and plant or sow trees before, along with, or after sowing agricultural crops. This "farming system" is no longer popular in Europe, but was widely practiced in Finland up to the end of the nineteenth century and was being practiced in a few areas in Germany as late as the 1920s (King 1968). Further, Nair (1993) attempted to give an account of the history of agroforestry, which has also been taken into consideration while formulating this account. Wood pastures (forestry combined with pasture and field crops) are reported to be practiced from Neolithic times (6000 BP) all over Europe. Dehesa and Montado (4500 years old) system, found in Mediterranean zone of Spain and Portugal, is characterized by savannah-like open tree layer, mainly dominated by evergreen oaks (*Quercus* spp.) and to a lesser extent by the deciduous *Q. pyrenaica* and *Q. faginea*. The herbaceous layer is comprised of cultivated cereals (oats, barley, wheat) or more commonly forage grasses grazed by diversified livestock types (sheep, goats, Iberian pigs, and cattle). The practice of fruit tree systems on arable land or grassland called pre'-verger or Streuobst, mixed with grazing animals is widespread and goes back to the Roman Empire. At that time, olive trees (*Olea europaea*) were predominantly intercropped with wheat (*Triticum aestivum*), and in the seventeenth century, orchards in England were also intercropped with wheat (Nerlich et al. 2013). Hauberg of the Siegerland is another specialized practice originated in northwestern Germany in the Middle Age when forest trees (oak and birch *Betula* spp.) provide wood and charcoal and after harvesting of trees cereals are grown for many years followed by a longer fallow with pastoral use until the next generation of forest has grown.

In Southeast Asia, the *Hununoo* of the Philippines practiced a complex and somewhat sophisticated type of shifting cultivation. While clearing the forest for agricultural use, they deliberately spared certain trees which, by the end of the rice-growing season, provided partial canopy of new foliage to prevent the excessive exposure of the soil to the sun. Trees were an indispensable part of this farming system to provide food, medicines, construction wood, and cosmetics (Conklin 1957). By the end of the nineteenth century, however, establishing forests or agricultural plantations had become an important objective for practicing agroforestry. In the beginning, the change of emphasis was not deliberate (Nair 1993). At an outpost of the British Empire in 1806, U Plan Hle, a Karen in the Tonze forests of Tharrawaddy division in Burma (now Myanmar) established a plantation of teak (*Tectona grandis*) and presented it to Sir Dietrich Brandis, the then Governor.

Brandis realized the detrimental effect of shifting cultivation on the management of timber resources and knowing the facts that there were several court cases against the villagers for encroaching the forest reserves, he encouraged the practice of regeneration of teak through *taungya* system based on the well-known German system of Waldfeldbau, which involved the cultivation of agricultural crops in forests. From this beginning, the practice became increasingly widespread and was introduced into South Africa as early as 1887 (Hailey 1957) and to the Chittagong and Bengal areas in colonial India in 1890 (Raghvan 1960). It must be noted that, once introduced, the system was practiced continuously in India. In the second decade of the twentieth century, the system became more and more popular with foresters as a relatively inexpensive method of establishing forests and as Shebbeare (1932) put it, "became a full and rising food." In 1920, it was adopted in Travancore (now Kerala), in 1923 in the United Province (now Uttar Pradesh), and in 1925 in the Central Provinces (Raghvan 1960). Later, it spread throughout Asia, Africa, and Latin America. Essentially, the system consists of growing annual agricultural crops along with the forestry species during the early years of establishment of the forestry plantation and still exists. *Shorea robusta*, *Tectona grandis*, *Dalbergia sissoo*, *Acacia catechu*, *Eucalyptus globulus*, *Populus deltoides*, and *Pinus patula* were some important tree species grown in this system. The land basically belonged to the forestry department and upon their large-scale lease, allowed the subsistence farmers to raise their crops and in turn protect the tree saplings.

In tropical America, many communities have traditional simulated forest conditions in their farms in order to obtain the beneficial ecological effects of forest structure. In Central America, for example, farmers since long imitated the structure and species diversity of tropical forests and have planted about two dozen species on a small piece of land configuring them in different storeys; coconut (*Cocos nucifera*) or papaya (*Carica papaya*) with a lower layer of bananas (*Musa* spp.) or citrus, a shrub layer of coffee (*Coffea arabica/robusta*) or cacao (*Theobroma cacao*), tall and low annuals such as maize (*Zea mays*), and finally a spreading ground cover of plants such as squash (Wilken 1977; King 1987). The Quezungal system in southern part of western Honduras (growing *Cordia alliodora* tree pollarded to 1.5 m along with food crops), the Riberno system in Peruvian Amazon (forest clearing followed by homegardens with multiple species), silvopastoral systems in Brazil (grazing under tree crops such as cashew, coconut, and *Copernicia prunifera* palm), and Amazonian homegardens are traditional practices (Hellin et al. 1999; Miller and Nair 2006; Peri et al. 2016).

The situation was little different in Africa. In southern Nigeria, yams, maize, pumpkins, and beans were typically grown together under a cover of scattered trees (Forde 1937). The Yoruba of western Nigeria, who have long experience of following intensive system of mixing herbaceous, shrub, and tree crops, claim that this system helps in maintaining the soil health (Ojo 1966). The parkland system of West African dryland involving multipurpose trees such as *Faidherbia albida*, *Vitellaria paradoxa*, *Parkia biglobosa*, *Adansonia digitata*, and *Balanites roxburghii* on pasture lands or along with food crops mainly millets and beans is predominant. Within the United States, many indigenous communities and practitioners continue to carry on traditional management practices, but others struggle to do so (Rossier and Lake 2014).

Thus, there are innumerable examples of traditional land use practices used in the past involving combined production of trees and agricultural crops on the same piece of land in many parts of the world (now called agroforestry). Jodha (1995) opined that traditional agroforestry systems manifest the indigenous knowledge and methods to benefit from complimentary uses of annuals and woody perennials on a sustained basis. It also indicates that the farmers have a closer association with trees than any other social land promoters of forests. Several developments in agricultural research and development during 1960s and 1970s were also instrumental in initiating organized efforts in agroforestry. Under the auspicious of the Consultative Group on International Agricultural Research (CGIAR), several International Agricultural Research Centers (IARCs) were established in different parts of the world to undertake research with the objective of enhancing the productivity of major agricultural crops and animals especially in tropics. Many factors and developments in the 1970s contributed to the general acceptance of agroforestry as a system of land management that is applicable to both farm and forest. Among these factors were reassessment of the development policies of the World Bank by its President, Robert McNamara; a reexamination by the Food and Agricultural Organization (FAO) of the United Nations of its policies pertaining to forestry; the establishment by the International Development Research Centre (IDRC) of a project for the identification of tropical forestry research priorities; a reawakening of interest in both intercropping and farming systems; the deteriorating food situation in many areas of developing world; the increasing spread of ecological degradation mainly deforestation; and the energy crisis. In the process, McNamara (1973) felt that the needs of the poorest of the poor were ignored and the hundreds of millions of the poor farmers suffered because of hunger malnutrition menace. It was against this backdrop of concern for the rural poor that the World Bank actively considered the possibility of supporting nationally oriented forest programs. As a result, it formulated a new Forestry Sector Policy paper, which is still being used as the basis for much of its lending in the forestry sub-sector. Indeed, the social forestry program, which expanded considerably and not only contained many of the elements of agroforestry but was designed to assist the ordinary farmer to increase farm production conserving the environment. FAO (1976) reexamined the forestry policies, and the concerns of the poorest, especially the rural poor, were adequately addressed in new policies. It also focused on the benefits that could accrue to both the farmer and the nation if greater attention were paid to the beneficial effects of trees and forests on food and agricultural production, and policy makers were advised to incorporate both agriculture and forestry into their farming system and “eschew the false dichotomy between agriculture and forestry” (King 1979).

As a result of this change in policy, FAO prepared a seminar paper “Forestry for Rural Development” (FAO 1976) and with funding from the Swedish International Development Authority (SIDA) organized series of seminars and workshops on the subject in the tropical countries and formulated and implemented a number of rural forestry projects throughout the developing world. In these projects, as with the

World Bank's social forestry projects, agroforestry plays a pivotal role (Spears 1987). FAO also utilized the eighth World Forestry Congress, which was held in Jakarta, Indonesia, in 1978, to focus the attention of the world's leading foresters on the important topic of agroforestry. The central theme of the Congress was "Forests for People," and a special section was devoted to "Forestry for Rural Communities."

Many of these studies and efforts, although not coordinated, provided important knowledge about the advantages of integrated production systems involving crops, trees, and animals. But, perhaps the most significant single initiative that contributed to the development of present-day agroforestry came from the International Development Research Centre (IDRC) of Canada. In July 1975, the IDRC commissioned John Bene, an indefatigable Canadian to lead the forestry research. Bene's team identified the research priorities and prepared a report in which it was concluded that first priority should be given to combined production systems which would integrate forestry, agriculture, and/or animal husbandry in order to optimize tropical land use (Bene et al. 1977). This report laid foundation stone for establishment of agroforestry as a new front, which is obvious from the contents of the report. It stated that a new front should have been opened in the war against hunger, inadequate shelter, and environmental degradation. This war could be fought with weapons that have been in the arsenal of rural people since time immemorial, and no radical change in their lifestyle was required. This could best be accomplished by the creation of an internationally financed council for research in agroforestry, to administer a comprehensive program leading to better land use in the tropics (Bene et al. 1977). This proposal was well received by international and bilateral agencies; subsequently, the International Council for Research in Agroforestry (ICRAF) was established in 1977. The ancient practice of agroforestry was institutionalized for the first time.

The development of high-yielding varieties of cereals and extension of related technologies through the joint efforts of some of the IARCs and implementation of national programs paved the way for Green Revolution (Borlaug and Dowswell 1988); however, its benefit could not be harvested by poor farmers because many of the technologies that placed a heavy demand on increased use of fertilizers and other costly inputs were beyond the reach of a large number of resource-poor farmers in the developing countries (Nair 1993). Most of the national programs were focused on individual crops such as wheat, rice, maize, and potato and production technologies for monoculture production systems. The resource-poor farmers often cultivated their crops in mixed stands of more than one crop, and sometimes crops and trees. In such circumstances the production technologies developed for individual crops would seldom be applicable. These shortcomings were widely recognized by the scientists and policy makers, and renewed interest was developed in the concepts of intercropping and integrated farming systems. The research efforts indicated that besides many advantages of intercropping on pest and disease problems. Higher yields could be obtained per unit area when multi-cropping systems were compared to sole cropping systems (Papendick et al. 1976). At that stage it was felt that more scientific efforts were needed with respect to understand crop physiology, agronomy, yield stability, biological nitrogen fixation, and plant protection in intercropping research (Nair 1979). Concurrently, the International Institute of Tropical Agriculture (IITA), an IARC in Ibadan, Nigeria, extended its work to include integration of trees and shrubs with crop production (Kang et al. 1981). Other research organizations had also initiated serious work on tree-based croping systems, for example, the integration of animals with plantation tree crops such as rubber and intercropping of coconut (Nair 1983).

This congruence of people, concepts, and institutional change has provided the material and the basis for the development of agroforestry since then. Although many individuals and institutions have made valuable contributions to the understanding and development of the concept of agroforestry since the 1970s, ICRAF (renamed in 1991 as the International Center for Research in Agroforestry) has played the most significant and leading role in collecting information, conducting research, disseminating research results, pioneering new approaches and systems, and, in general, through presentation of hard facts. The Center coined the term “agroforestry”and called for global recognition of the key role trees play on farms.

During the 1980s, ICRAF operated as Information Council focused on Africa. It joined the Consultative Group on International Agricultural Research (CGIAR) in 1991 to conduct strategic research on agroforestry at a global scale, changing its name from Council to Center. After joining the CGIAR, the Center explicitly linked its work to the goals of the CGIAR – reducing poverty, increasing food security, and improving the environment – through overcoming land depletion in smallholder farms of subhumid and semiarid Africa and searching for alternatives to slash-and-burn agriculture at the margins of the humid tropical forests. In implementing this strategy, the Center expanded into South America and Southeast Asia while strengthening its activities in Africa and formally adopted an integrated natural resource management framework for all its work and institutionalized its commitment to impact by creating a development group dedicated to move research results onto farmers’ fields; and in 2002, the Center acquired the brand name the “World Agroforestry Center” (www.icraf.cgiar.org).

As discussed earlier, though having traditional practices of growing trees and crops together and rearing cattle on farm, the organized research in agroforestry was initiated in India also with the establishment of the All India Coordinated Research Project (AICRP) on agroforestry in April 1983 by the Indian Council of Agricultural Research (ICAR). The Council took lead in conducting systematic research in agroforestry initially through several coordinated projects and later by establishing National Research Center for Agroforestry (NRCAF) in 1988 at Jhansi to cater basic, strategic, and applied research needs in the field of agroforestry. The AICRP on agroforestry, a large agroforestry network operational since 1983, was transferred to NRCAF in 1997 by empowering director NRCAF as the Project Coordinator of this splendous program. At present, the AICRP is being operated at 25 State Agricultural Universities (SAUs), 11 ICAR institutes, and one Indian Council of Forestry Research and Education (ICFRE) institute. In the last three decades, several agroforestry systems have been developed in India which have gone to farmers’ fields and provided livelihood support to resource-poor farmers. Now, the NRCAF has been upgraded as ICAR-Central Agroforestry Research Institute (CAFRI) and is recognized worldwide for its research and development capabilities, agroforestry database and information repository, and natural resource management on watershed basis (http://www.cafri.res.in). The mission of the institute is to improve quality of life of rural people through integration of perennials on agriculture landscape for economic, environmental, and social benefits. Its aim is to develop sustainable agroforestry practices for farms, marginal land, and wastelands in different agroclimatic zones of India; coordinate network research for identifying agroforestry technologies for inter-region; conduct training in agroforestry research for ecosystem analysis; and transfer technology in various agroclimatic zones. The mandate is to integrate woody perennials in the farming systems to improve land productivity through conservation of soils, nutrients, and biodiversity to augment natural resource conservation, restoration of ecological balance, and alleviation of poverty and to mitigate risks of weather vagaries. Now, besides World Center of Agroforestry (ICRAF) and CAFRI, agroforestry as a decipline of science has reached throughout the world and is being taught as subject in several agricultural and forestry institutes such as the Center for Agroforestry at the University of Missouri; Center for Subtropical Agroforestry, University of Florida; and centers of several agricultural and forestry universities/institutes in India.

3 Concepts of Agroforestry

It is clear from above discussion that agroforestry is a new name for a set of ancient practices. The word and concept attained a fair level of acceptability in international land use parlance in a rather short time. In the beginning (during 1970s and early 1980s), undoubtedly, a lot of ambiguity and confusion existed about agroforestry concept. The situation was reviewed in an editorial, appropriately titled "What is Agroforestry?" in the inaugural issue of *Agroforestry Systems* (Vol 1, pp. 7–12, 1982), which contained a selection of "definitions" of agroforestry, proposed by various authors. In summarizing these definitions, Bjorn Lundgren (1982) of ICRAF stated that two characteristics common to all forms of agroforestry and separate them from the other forms of land use, namely:

- The deliberate growing of woody perennials on the same unit of land as agricultural crops and/or animals, either in some form of spatial mixture or sequence.
- There must be a significant interaction (positive and/or negative) between the woody and non-woody components of the system, either ecological and/or economical.

These ideas were later refined through "in-house" discussions at ICRAF, and the following definition of agroforestry was suggested (www.icraf.org):

> "Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence"

This definition, though not perfect in all aspects but has been increasingly used in ICRAF and other publications. In agroforestry systems, there are both ecological and economical interactions between the different components (Lundgren and Raintree 1982). Even the simplest agroforestry system is more complex, ecologically (structurally and functionally) and economically than a mono-cropping system.

Today, there is a consensus of opinion that agroforestry is practiced for a variety of objectives. It represents an interface between agriculture and forestry and encompasses mixed land use practices. These practices by and large have been developed based on the special needs and ecological conditions of the farmers in developing countries. Social objectives are very important in their adaptations. Terms like "social forestry," "farm forestry," and "community forestry" are found commonly used in literature. Social forestry is considered to be the practice of using tree plantations for pursuing social objectives, usually for the betterment of the poor through delivery of the benefits (fuel wood, fodder, small timber, shade, financial help, etc.) to the local people. Some local people call it "trees growing by people for the people." Community forestry, a form of social forestry, refers to the tree planting activities undertaken by involving community and plantation is done on community (common property) land for the benefit of entire community. It is based on the local people's direct participation in the process, either by growing trees themselves or by processing the tree products locally. Nowadays many self-help groups earn livelihood by developing government-sponsored programs through value addition to agroforestry products. Farm forestry, a term, commonly used in Asia, indicates tree plantations on farms, usually in association with crops.

The major distinction between agroforestry and the other terms seems to be that in agroforestry emphasis is on land use system where woody perennials are grown in association with crops/grasses and or animals for multiple products and services; the other terms refer to mainly tree plantation, often as woodlots. In literature, all kinds of tree plantations refer to growing and using trees to provide food, fuel wood, fodder, medicine, building materials, thatching, and cash income. Trees of all these systems are used for multiple uses, which is the main concept of agroforestry. Only blurred lines, if any, separate them and they all encompass agroforestry concepts and technologies. As characterized by ICRAF (2008), agroforestry helps in diversifying and sustaining production of the broad spectrum of agricultural commodities for enhanced economic, environmental, and social benefits by integrating trees on farms and in the agricultural landscape. Today, agroforestry represents the modern, science-based approach to harnessing the sustainability attributes and production benefits of such time-tested practices, and its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use is receiving increasing attention in developing programs around the world (Maffi 2007).

4 Agroforestry Systems/Practices

Agroforestry systems are widely based on nature and arrangement of the components and ecological or socioeconomic criteria. But no single classification scheme can be accepted as universally applicable. Therefore, classification of agroforestry systems will have to be purpose oriented. The complexity of the problem can be reduced if the structural and functional aspects of the systems are taken as the criteria for categorizing the systems and agroecological and socioeconomic aspects as the basis for further continuing. Since there are only three basic sets of components (woody perennials, herbaceous plants, and animals) to be managed, the first step of classification may be based on these components.

During the past four decades, agroforestry has come of age. Numerous indigenous forms of growing trees and crops together, sometimes with animals, were brought under the realm of modern scientific land use scenarios due to the efforts of local, national, and international organizations. Communities around the world have practiced diverse and evolving forms of agroforestry for time immorial (Nair 1989; Birkes et al. 2000; Parrotta and Trosper 2012), and both indigenous and non-indigenous practitioners have taken advantage of indigenous and traditional ecological knowledge for developing improved practices of great value. Many workers (Nair 1993; Dagar et al. 2014b; Rossier and Lake 2014; Dagar and Tewari 2016a; Nair et al. 2016) have mentioned about the utilization of indigenous knowledge among the communities of Asia, Europe, Africa, American Indians, Alaska Natives, Caribbean and Pacific Islanders, and other regions. Because indigenous groups have lived in the same areas for long periods of time, each generation has built on the knowledge of the previous generation through observation and experimentation and implemented in these local practices. In this manner, indigenous groups have evolved intricate ways to manage bio-culturally diverse ecosystems, which are time tested. These ecosystems are managed to provide food, fuel, building materials, agricultural and plant-tending tools, hunting and trapping equipment, baskets, medicines, and ceremonial spaces essential to life and maintaining cultural traditions. Many agroforestry practitioners across the globe have tried to learn from these complex systems and inculcated the useful information while developing the modern systems in many cases (Nair and Garrity 2012a; Dagar et al. 2014b; Dagar and Tewari 2016a).

There is subtle difference between “system” and “practice.” A system is a specific local example of a practice. There are an enormously large number of agroforestry systems, but the specific practices that constitute them are few (Nair 1985, 1989; Young 1989). These two terms that used to be distinguished in the early stages of agroforestry development are now used rather synonymously. According to Nair’s original classification scheme (Nair 1985), the vast majority of agroforestry practices that have been discussed and researched fall under “conventional” categories, later expanded as five agroforestry systems subgroups (Nair 2012). The three original major groups of systems included agrisilvicultural (crops + trees), silvopastoral (trees + pasture/animals), and agrosilvopastoral (crops + trees + pasture/animals). The five expanded system groups include alley cropping and other forms of tree intercropping, multi-strata systems of homegardens and shaded perennials, silvopasture (grazing and browsing forms), protective systems (such as shelterbelts, windbreaks, and soil conservation systems), and agroforestry tree woodlots for fuel and fodder production and/or land reclamation. In literature, particularly in India, some other terms referring specific associations such as silvipasture, agri-horti, silvi-horti, horti-silvi, and so on have been found used. As stated above, traditional/indigenous systems, which are time tested and have played significant role in developing modern systems, are discussed in brief here explaining how these have helped in evolving modern agroforestry systems.

4.1 Traditional/Indigenous Agroforestry Systems

During the early stages of agroforestry development, description of traditional practices involving trees, crops, pasture, and animals dominated the agroforestry literature. Nair (1989) was among the pioneers to compile these systems mostly from tropical and subtropical regions in the form of a book entitled *Agroforestry Systems in the Tropics* followed by immense literature published in the Journal *Agroforestry Systems*. Most of the present-day systems so-called modern systems are basically not new systems but modified version of indigenous systems. They all have been built upon the native assets of land, water, and other resources, relying on the traditional time-tested knowledge and land races adapted to different edaphic and ecological situations. Each system is unique in terms of its structural, production, environmental, and sociocultural attributes. Recently, 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 (for more details see Nair et al. 2016).

Some of the indigenous and traditional systems/practices, having diverse characteristics, are listed in Table 2.1. Most of these are anecdotal and indigenous; in some cases, enough research has been carried out in the recent past. To understand their basic principles, the characteristic features of some of these practices have been described here in brief.

4.1.1 Shifting Cultivation (Slash-and-Burn System)

Shifting cultivation, one of the most primitive traditional agroforestry practices, is prehistoric and partly a response to agroecological conditions in various regions. It refers to farming system in tropics and subtropics in which land under natural

Table 2.1 Some common traditional agroforestry systems/practices[a]

Main system	Practices	Agroecological adaptations/remarks
Agri-silvicultural (trees with crops)	*Rotated in time (sequential practices)*	
	Shifting cultivation	Trees left after clearing of forests or planted to grow during fallow; mainly in tropical regions
	Taungya	Agricultural crops grown during early age of plantation; in most of hilly regions; widely followed
	Improved fallows	Shrubs (mostly legumes) and crops grown together, shrubs retained as fallows for 2–3 years to improve the soil, and again crops are grown. Herbaceous cover crops are also grown
	Relay intercropping	Shrubs and crops planted together each year; mostly tropical regions
	The Quezungal system	In Central America, *Cordia alliodora* is a common multi-purpose tree, pollarded to 1.5 m, and regenerates naturally; crops such as maize, sorghum, and beans are grown
	The Riberno system	In the Peruvian Amazon, after forest clearance, agricultural crops mainly cassava, yam, plantains, rice and fruits are cultivated along with retained trees
	Spatially mixed (simultaneous practices)	
	Trees on crop land (parkland systems)	Scattered trees on crop lands, e.g., Khejri (*Prosopis cineraria*) on crop fields mainly millet in arid India; *Acacia leucophloea* and many MPTs on crop fields of Tamil Nadu in India
	Plantation crop combinations	Plantation, shade trees with partial shade-tolerant crops, mainly tuber crops or shade trees and commercial crops like coffee or tea; mainly tropical regions
		In the Amazon region, fruit trees, various palms, cacao, Brazil nut (*Bertholletia excelsa*) and agricultural crops (cassava, yams, beans, plantain, etc.) are cultivated. These also become part of their homegardens
	Homegardens (multi-strata systems)	Multi-strata trees like coconut in upper storey, clove, cinnamon in middle storey, tuber crops or pineapple and vegetables as ground crops and vines like black pepper and cucurbits; mostly around homesteads in tropical regions
	Specially zoned (simultaneous practices)	
	Alley cropping	Hedgerow intercropping with woody species which are pruned frequently for fuel, fodder or green manure; mainly on sloping high rainfall areas in almost all regions
	Boundary planting	Trees on field boundaries of agricultural fields or along canals to check seepage; and also as live fences
	Strip planting	Plantations with corridor farming or on acre line to control rise in water table in waterlogged areas; and also to check sand dune movement
	Shelterbelt	Plantations to shelter crops from wind and also as live fences
	Woodlots	Trees for cut-and-carry purposes to be used as fodder, fuel and mulching
	Farming in forests	Cultivation of crops in natural forests; many areas in Europe. For example, in Canada ginseng is commonly cultivated in forests and wild mushrooms are collected as food item

(continued)

Table 2.1 (continued)

Main system	Practices	Agroecological adaptations/remarks
Silvopastoral (tree with pasture and or animals)	*Spatially mixed (simultaneous practices)*	
	Trees on rangeland or pasture (parkland systems)	Scattered or systematically planted MPTs or shrubs mainly of fodder use on pasture lands; mainly in dry regions
	Perennial crops with pasture	Plantation crops like coconut and cashew nut sometimes fruit trees on pasture lands; mainly in tropical regions
		In Brazil, grazing under tree crops such as cashew, coconut and carnauba palm (*Copernicia prunifera*) is common practice
	Specially zoned (simultaneous practices)	
	Boundary plantation	Trees mainly of fodder use on boundary of pasture lands; live fences and streamside protection
	Shelterbelts	MPTs to shelter pastures and animals from wind and snow; mainly in temperate regions
	Woodlots	MPTs used as stock fodder, fodder banks, soil protection, etc. in pastoral systems. In Europe, animals are commonly left for grazing in woodlots
Agro-silvopastoral (trees with crops and pasture/animals)	*Specially mixed (simultaneous practices)*	
	Homegardens with animals	In Tanzania, tall trees like *Cordia abyssinica, Albizia* spp. and *Diospyros mespiliformis* in upper storey; banana and coffee in the 2nd storey; and food crops, fodder, cardamom and medicinal herbs in lower storey
	Global heritage of East Africa (the Chagga, Matengo Ngoro-Pit, and Ngitti systems)	
	Compound farms of West Africa	Food crops like yams, plantain, maize, etc. are grown with fruit trees (e.g., *Treculia africana*, *Dacryodes edulis*, and *Pterocarpus* sp.) and animals
	The parkland system in West Africa	MPTs like *Faidherbia albida, Vitellaria paradoxa*, *Parkia biglobosa*, *Adansonia digitata*, and *Balanites roxburghii* are cultivated along with staple cereals mostly millets and extensive silvopastoralism with free-roaming animals
	Spatially zoned (simultaneous practices)	
	Multipurpose woody hedgerows	Woody hedges for fodder, fuel wood, mulch, soil conservation; in most areas as cut-and- carry system
	Multipurpose woodlots	MPTs are grown widely (mainly on community land) as woodlots for wide range of uses
Others/Site-specific	Entomo-forestry	Trees and beekeeping; in Africa some insects such as mopane worm are reared on mopane trees as food; some insects are reared as commercial purposes such as lac insect on *Butea monosperma* and silkworm on *Morus alba* in Asia
	Aquaforestry	Trees on boundary of fish/shrimp ponds
	Multi-enterprise farming	Many components such as trees, fruits, animals, poultry, fish, cereals, vegetables, and bees are integrated together for getting sustained income and livelihood
	Reclamation/rehabilitation/recreational forestry/biodrainage plantations	Trees, grasses, and crops for reclamation of degraded lands including eroded, salt-affected, and waterlogged areas and to rehabilitate mine-spoil areas; as degraded mangrove areas; as biodrainage plantation to lower down water table in waterlogged areas; etc.

[a]Compiled from various sources. More details and references are available in text

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 reduced to even 3–5 years. The practice is over 9000 years old, believed to have originated in the Neolithic period around 7000 BC (Maithani 2005), and is still extensively practiced in Northeastern Himalayan Region and other humid and hilly parts of Indian subcontinent.The system is addressed with different names in different parts of the world. In many parts, shifting cultivation and taungya system are considered same.

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 including northeastern regions of India. Estimates of area under shifting cultivation vary. According to one estimate (FAO 1982), it extends over 360 million ha supporting over 250 million people. Crutzen and Andrea (1990) estimated the system being practiced by 200 million people over 300–500 million ha. Haokip (2003) mentioned that in the world about 500 million people are estimated to practice shifting cultivation in 410 million ha area (forest land) and in Asia alone, about 80 million people spread over nearly 120 million ha are practicing this system. In India, about 60,000 families in 48 districts are cultivating 2.27 million ha area as shifting cultivation (FSI 1997). Though exact figures about total area under shifting cultivation are not available, it is still applied in about 40–50 countries (Mertz 2009) and constitute an important part of the 850 million ha of secondary forest in tropical Africa, America, and Asia (FAO 2005).

The practice is thought to account for about one-third of the deforestation in the Amazon, while cattle ranching is responsible for at least half of the deforestation (Serrato et al. 1996). Rural population in many parts of the eastern Amazon is so dense that fallow periods between cultivation cycles are too short to allow soils to recuperate. Lundgren (1978) reported from 18 locations around the tropics that an average of 8.9 Mg ha^{-1} yr^{-1} litter was added from natural forests, amounting to average nutrients (kg ha^{-1} yr^{-1}) of 134 N, 7 P, 53 K, 111 Ca, and 32 Mg, and the quantity of nutrients lost from such a system was negligible. Clearing and burning the vegetation leads to a disruption of this closed nutrient cycle. The changes in soil due to clearing and burning of vegetation result in sharp increase of available nutrients so that the first crop is very good. Afterward, the soil becomes less and less productive and crop yields decline. The main reasons for the decline in crop yields are soil fertility depletion, increased weed infestation, deterioration of soil physical properties, and increased insect and disease attacks (Sanchez 1976).

Despite remarkable similarity of the system practiced in different parts of the world, marginal differences do exist and are often dependent on the environmental and sociocultural conditions of the locality and the historical features that have influenced the evolution of land use systems over the centuries in different parts of the world. *Jhum* cultivation in Northeastern Himalayan Region is a complex system with wide variation and depends upon ecological variations in the area and cultural diversity among various tribal clans. There are some tribes who have ecological knowledge and have developed the system to be quite sustainable. One of the common features of shifting cultivation in the region is growing of mixed crops after partial or complete removal of vegetation. Common crops such as potato (*Solanum tuberosum*), rice (*Oryza sativa*), maize (*Zea mays*), tapioca (*Manihot esculenta*), colocacia (*Colocasia esculenta*), ginger (*Zingiber officinale*), sweet potato (*Ipomoea batatas*), millets (species of *Panicum*, *Eleusine*, *Pennisetum*), etc. are grown in isolation or mixed crops along with *Pinus kesiya* or other retained trees depending upon the need. Another important attribute of the system is secondary succession of vegetation during fallow period. The Angamis tribe from Nagaland since long has practiced nitrogen-fixing tree Alder (*Alnus nepalensis*)-based sustainable *Jhum* system that has been reported to provide 57 food crops to supplement the staple food crop rice (Singh et al. 2014). The system provides about five dozen food crops to supplement the staple crop rice. Alder improves soil fertility by fixing atmospheric nitrogen into the soil through *Frankia*. The nitrogen fixed varied between 48.3 (60 trees per ha) and 184.8 kg per ha (625 trees per ha). The fallen leaves act as mulch and add humus to the topsoil. Mixed cropping is repeated in the second year. The field is then left fallow for about 4 years. Alder tree is pollarded first time at a height of 2 m when 7–10 years old and subsequent pollarding is performed after 4–6 years.

The Konyak tribes in Nagaland also have sound ecosystem knowledge and have at times about 3000 seedlings of *Macaranga denticulata* per hectare of land. They gradually reduce the density during the fallow period and keep optimum number suiting to their cropping density. These both tribes also keep other multipurpose trees such as *Trema orientalis*, *Sapium baccatum*, *Schima wallichii*, and species of *Grewia* and *Quercus* in the Jhum fields. In the Konyak Jhum field, more than 40 species can be seen. They have sound knowledge of mixing rice and colocasia by which the sloping land is covered under vegetation for a greater part of the year. They also manage fallows (for 7–9 years) cycling twigs and leaves in the soil to increase the soil fertility. In Meghalaya, bun method of cultivation is unique, where twigs and branches of forest trees along with weed biomass (from the surrounding areas) are kept in heaps at regular intervals across slopes. The buns are usually 2–4 m long, 1–2 m wide, and 0.2–0.4 m in height spaced at 1–2 m depending upon soil depth and are covered with a thin layer of soil in order to burn the entire biomass under anaerobic condition converting it gradually into ash. Further, zabo indigenous farming practice in Nagaland is a combination of forest, agriculture, animal husbandary, and pisciculture on highly sloping land. Hill slope is kept under trees, mid slope is used for construction of silting ponds and water harvesting tanks, and land down slope for animals and terraced rice fields. Ponds are desilted every year and material along with forest litter is spread in the fields for manuring. Entire animal dung is cycled in the fields. This way, around 80–100 kg N, 15–25 kg P, and 50–75 kg K per ha, besides organic matter and micronutrients, are added to the soil annually. Farmers rear fish and cultivate rice without adding any inorganic nutrients and get enough fish for the family, and soil loss due to erosion is also below the critical limit.

In Pacific Islands, shifting cultivation is managed through manipulating the different storeys of trees.Various tropical fruit-and-nut trees are maintained as upper storey; shorter trees as second storey; crops, mostly tuber crops, in the lowest storey; and ornamentals along borders (Elevitch 2011). At times, upper storey fruit trees are pruned to allow sunlight for lower storey species and allowed to return to fallow for a period ranging from 4 to 10 years, retaining only fruit trees. A variety of tree products, fruits, food, vegetables, fiber, flowers for decoration, beverages (Kava is used as social beverage), and medicine are obtained from the system.

Shifting cultivation in Vietnam is characterized as production of food crops on land with slopes over 45%. It is still practiced due to the problem of food security in mountainous regions. It is a traditional practice associated with resource poor people and linked with cultural and spiritual life of people. The economy of ethnic minorities still depends basically on shifting cultivation. About two million people of 54 different ethnic groups practice slash- and-burn agriculture in the mountainous area of Vietnam. They describe this form of agriculture as "*nuong ray*" and people are also called by this name. There are three types of practices. In the first, rice (*Oryza sativa*) is the main crop grown which yields 2 Mg ha^{-1}in the third year when the field is abandoned and farmers move to another site. In the second type, seeds of *Melia azedarach* are sown and site is burnt. Usually rice is sown with *Melia* (1000–1500 plants per ha) after burning. After 3 years when cropping is stopped, *Melia* is established along with bamboo as natural crop. In the third type, *Cinnamomum* is planted with rice and cassava (*Dioscorea* spp.) in the first 3 years. Shade trees are also planted. Although under low population pressure earlier, this system was sustainable but now it is the main cause of deforestation, soil erosion, and land degradation. The traditional farmers in low-lying areas of South Vietnam grow *Melaleuca leucadendra* with rice on acid sulfate soils having pH as low as 2.3.

In Brazil (Latin America), the Riberno system in Peruvian Amazon, also known as Swidden fallow system, forest clearance is followed by kinds of homegardens, where no definite planting pattern is followed in multiple configurations. Food crops (yams, plantains, tubers, maize etc.) are cultivated with fruit and other trees such as *Treculia africana*, *Dacryodes edulis*, and *Pterocarpus* sp., and animal products are made for home consumption. Lojka et al. (2016) reported a viable multistrata agroforestry system as an alternative to slash-and-burn farming in the Peruvian Amazon, where between 1999 and 2005, deforestation rates varied between 632 and 645 km^2 per year. The key component for establishment of multi-strata systems is *Inga edulis*, a tree that besides producing marketable fruits can improve soil fertility and suppress noxious weeds during the first year of establishment. Other promising and fast-growing trees include *Dipteryx micrantha*, *Schizolobium parahyba*, *Parkia* spp., *Tabebuia impetiginosa*, and *Simarouba amara* among timber species and *Annona muricata*, *Spondias dulcis*, and *Poraquei basericea* among fruit trees. Annual crops such as cassava, maize, beans, etc. along with pineapple (*Ananas comosus*) form the system viable (Bortl 2011; Lojka et al. 2016). This system proved to be highly beneficial as compared to traditional system.

4.1.2 Taungya

The *taungya* system in the tropics is like an organized and scientifically managed shifting cultivation, a forerunner to agroforestry. The word is reported to have originated in Burma (now Myanmar) and means hill (*tauang*) cultivation (*ya*) (Blanford 1958). Earlier it was a local name for shifting cultivation and later subsequently used to describe afforestation as well. Today the system is known by different names (King 1987; Nair 1993). In German-speaking countries, it is called *haumfeldwirtschaft*, *brandwirtschaft*, or *waldfeldbau*. In francophone countries, it is referred to as *cultures sylvicole et agricole combines*, *culture intercalaires*, *method sylvo agricole*, *systeme sylvo-bananier*, *plantation sur culture*, etc. The Dutch name is *bosakkerbouw*. In Puerto Rico, it is called the *parcelero* system, in Brazil *consorciarcao*, in Libya *tahmil*, in the Philippines *kaingining*, in Indonesia *tumpangsari*, in Malaya *lading*, in Kenya the *shamba* system, in Jamaica *agricultural contractors' system*, in Sri Lanka *chena*, in Tanzania *the licensed cultivator system*, and in India variously described as *dhya*, *jhooming*, *kumri*, *punam*, *taila*, and *tuckle*. In the greatest number of countries in the world, it is called *taungya*. In 1968 (when agroforestry was not defined), King (1968) suggested the genetic term "agrisilviculture" be generally employed to it. It can be considered a step in the process of transformation from shifting cultivation. It is not merely the temporary use of piece of land and a poverty level wage, but a chance to participate equitably in diversified and sustainable agroforestry economy. There are numerous reports describing *taungya* practices of different regions, but research data on impact studies and changes on the soil fertility and management aspects are, however, scarce. Alexander et al. (1980) based on 2 years' data on the Oxisols of Kerala mentioned disadvantage of *taungya* causing erosion hazard caused by soil preparation during cultivation for the agricultural crops. The surface horizons became partly eroded and subsurface horizons were gradually exposed. The addition of crop residues to the soil surface was found to be a very effective way of minimizing soil loss and exposure. In India, *Tectona grandis*, *Dalbergia sissoo*, *Eucalyptus* spp., and *Shorea robusta* are widely grown with various crops, but some site-specific species such as *Populus deltoides* in Indo-Gangetic plains; *Anacardium occidentale*, *Bombax ceiba*, and *Acacia leucophloea* in Andhra Pradesh; *Shorea assamica* and *S. robusta* in Assam; *Schima wallichii* and *Cryptomeria japonica* in West Bengal; *Santalum album* and *Cassia siamea* in Karnataka; and *Pterocarpus dalbergioides* in Andamans are reported frequently grown with local crops.

In a study in southern Nigeria involving *Gmelina arborea* with maize, yam, or cassava, Ojeniyi and Agbede (1980) found that the practice usually resulted in a slight increase in soil N and P, a decrease in organic carbon, and no change in exchangeable base and pH compared with sole stands of *G. arborea* and in a separate study in three ecological zones of southern Nigeria. Ojeniyi et al. (1980) concluded that the practice of inter-planting young forest plantations with food crops would not have any adverse effect on soil fertility. The long-term effect of the practice on soil fertility will, however, largely depend on the management practices adopted at the time of the initial clearing as well as subsequent reestablishment phase. Though there are reports to suggest alternative or improvement to *taungya* (e.g., forest village scheme in Thailand reported by Boonkrid et al. 1984) and the system is still popular in some places as a means for plantation establishment, it continues to be a relatively unimproved land use practice. 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. Oluwadare (2014) after analyzing selecting 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 the form of extension visits. All these studies confirm the sustainability of the system and severity of livelihood of resource-poor farmers.

4.1.3 Improved Fallows

Improved fallows are also land resting from cultivation and the deliberate planting and managing of fast-growing species of trees, shrubs, and herbaceous cover crops – usually legumes – for rapid replenishment of soil fertility. Improved fallows are rapidly spreading in several regions of the tropics as a sensible way for in situ accumulation of large quantities of N in vegetation and soil, as well as for providing sustainability enhancing services (Sanchez 1999). Research on improved fallows increased after the mid-1980s with the development of what is known as the second soil fertility paradigm, which is based on sustainability considerations. Many lessons have emerged from short-term improved fallows (<5 years' duration). These include the diversity of farm sizes where improved fallows are used, the advantage of sequential versus simultaneous systems, the utilization of dry seasons unfavorable for crop production, the comparative advantages of woody versus herbaceous leguminous fallows, the magnitude of N accumulation, the strategic use of N fertilizers, and the importance of P (Sanchez 1999; Kwesiga et al. 1999, 2005; Franzel et al. 2001). Other key services provided by fallows include fuel wood production, recycling of nutrients besides N, provision of a C supply to soil microorganisms, weed suppression, and improved soil water storage.

Most reviews on alternatives or improvements to shifting cultivation contain recommendations on tree species considered suitable to alternate and/or intercrop with agricultural species, grow fast, and efficiently recycle available nutrients within the system, thus shortening the time required to restore fertility. Nair (1993) has included about 44 species of perennial legumes used in Asian farming systems which may help in improving the fallow. These include species of *Acacia*, *Albizia*, *Alnus*, *Cajanus*, *Calliandra*, *Casuarina*, *Erythrina*, *Faidherbia*, *Flemingia*, *Gliricidia*, *Inga*, *Leucaena*, *Parkinsonia*, *Pithecellobium*, *Prosopis*, *Robinia*, and *Sesbania.* In northwestern India, *Sesbania cannabina/aucleata* grown under irrigation for 65 days between wheat and rice crops could add 7.3 Mg ha^{-1} dry matter and 165 kg N ha^{-1} (Bhardwaj and Dev 1985). Thus, nitrogen-fixing species may play vital role in improving the fallows. Present-day shifting cultivators do not often shift their residences as far apart as did previous generations because of shrinking land area per family due to rise in population. This has forced them, as well as the researchers concerned about their plight to look for land management systems by which they can get something from the land even during the so-called fallow phase. Thus, intercropping under or between fast-growing trees in fallow phase must be one of the approaches while finding alternative to shifting cultivation. It seems logical to accept that managed permanent cultivation systems such as improved *taungya*, homegardens, plantation crop systems, alley cropping in hilly regions, and tree incorporation on farm, and grazing lands are most of the alternatives to solve the problems.

Improved fallows are considered successful because of three sets of 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 stabilizing soil, carbon sequestration, etc.), and the development of an institutional mechanism, an adaptive research and dissemination network of government, NGO, and farmer organizations, to sustain adoption of the practice (TECA 2003). The crops and other food items are almost organic or with limited use of fertilizers and insecticides (produced from organic source, e.g., 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. This must be overcome though large-scale seed orchards and nursery development before impact at the scale of millions of farmers can take place.

The decline in soil fertility in smallholder systems is a major factor inhibiting equitable development in much of sub-Saharan Africa. Smalling et al. (1997) estimated that soils in sub-Saharan Africa are being depleted at annual rates of 22 kg ha^{-1} for nitrogen, 2.5 kg ha^{-1} for phosphorus, and 15 kg ha^{-1} for potassium. In many areas, farmers periodically fallow their land, i.e., allow it to lie idle for one or more seasons primarily to restore its fertility. As population increases, fallowing and fallow periods are reduced, continuous cropping becomes more frequent, and crop yields often decline. Cultivation is extended to marginal areas, causing soil degradation. With consistent efforts of the scientists (Buresh and Cooper 1999; Sanchez 1999; Franzel et al. 2001; Amadalo et al. 2003; Kwesiga et al. 2005), many farmers adopted successfully the short fallows and could sustain the crop yields improving the soil properties in deforested areas. They raised one or more woody species in short fallows of 2–5 years along with field crops like maize. The woody species included *Sesbania sesban*, *Tephrosia vogelii*, *Cajanus cajan*, and *Acacia angustifolia* in eastern Zambia, Zimbabwe, and southern Malawi; *Calliandra calothyrsus* in Kenya and Cameroon; *Leucaena leucocephala* in the Philippines and many African countries as alley crop; *Senna siamea* and *Flemingia macrophylla* in Ghana; and *Acacia angustifolia*, *A. mangium*, *Inga edulis*, *Sclerolobium paniculatum*, *Gliricidia sepium*, and *Leucaena leucocephala* in Amazonia, Brazil, Tanzania, Nigeria, and many other countries. Other species are *Tephrosia candida*, *Desmodium uncinatum*, *Crotalaria juncea*, *C. grahamiana*, *C. paulina*, and *C. striata*. In many locations herbaceous cover consisting of *Canavalia ensiformis*, *Calopogonium mucunoides*, *Mucuna pruriens*, *Dolichos lablab*, *Macroptilium atropurpureum*, and *Crotalaria* spp. is frequenly grown to improve the fallow, which also control weed infestation.

Evolutionary trends in tropical systems show that management intensities capable of sustaining productivity are usually introduced only after considerable depletion and degradation of resources (especially of the nonrenewable soil) have taken place. As we know that the role of fallow period in improving soil properties is well known but if this period is reduced, there is sharp deterioration of the soil and productivity status of the system. Kang and Wilson (1987) developed a pathway indicating points at which intervention with planted fallow or other agroforestry methods could be introduced thus preventing further resource degradation. Awareness of the soil-rejuvenating properties of different species in the fallow system, manipulation of species in the short fallow in order to ensure fertility regeneration, retention of useful soil fertility restorer trees, introduction of improved techniques like alley cropping, and concepts of development of the climax multistorey production system based on agroclimatic condition of the region are some of the features which are important. If one adheres to the evolution pattern of shifting cultivation and sustainability, high productivity can be achieved only when conservation and restoration measures are introduced before resources are badly depleted.

It is evident that shifting cultivation has become unsustainable primarily because of reduced *jhum* cycle owing to the increase in population pressure. Sustainable farming strategies and alternatives to ensure the livelihood security of the native people are the need of the day. There is urgent need of settling the land tenureship issue educating the people about the adverse impacts of short *jhum* cycles. Eco-development plans for areas under shifting cultivation should be developed on priority on site-specific basis involving sustainable agroforestry practices. Determining the population supporting capacity of a *jhum* stand may be one of the major aspects for checking the degradation of the environment and depletion of the resources. Overall strategy should be developed which ensures improving livelihood of people by efficient utilization of natural resources including land, water, biodiversity, and external input in a practical and profitable manner enhancing the environmental safety. Integrated approach involving crop, fruit, animal husbandry, fishery, and forestry with appropriate conservation measures for natural resources would be most effective in overall development of the shifting cultivation areas. Borthakur (1992), Ramakrishnan (1992), Tripathy and Barik (2003), Tomar et al. (2012), and Singh et al. (2014) have suggested several measures to deal with the problems related to shifting cultivation.

4.1.4 Homegardens

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, 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. Homegardens are rich in biodiversity. A farmer in Thailand demonstrated the system as an environmentally sustainable alternative to conventional agriculture where he planted and maintained more than 500 species of plants in 1.9 ha area (FAO 1990). Much has been written about homegardens and numerous terms have been used by various workers. These include mixed-garden horticulture, housegarden, Javanese homegardens, compound farm, kitchen garden, household garden, and homestead agroforestry (Nair 1993).

Javanese homegardens (*Pekarangan talunkebun*) provide an illustrative example of the diversity and complexity of tropical homegardens. Starchy food plants (cassava and *ganyong- Canna edulis*), vegetables, and spices dominate the lower two layers (up to 2 m); banana, papaya, and other fruit trees dominate the next two layers (2–5 m). Fruit trees or other cash crops such as cloves also dominate the five to ten meters' layer. Coconut and other multipurpose trees dominate the top layer (higher than 10 m). Homegardens of Java generate relatively good income and are good source of nutrients. Plantation crops such as coconut, cacao (*Theobroma cacao*), coffee (*Coffea arabica/robusta*), areca nut (*Areca catechu*), and black pepper (vine) (*Piper nigrum*) often are the dominant components of many homegardens of humid tropics. Fruit such as banana (*Musa paradisiaca*), papaya (*Carica papaya*), mango (*Mangifera indica*), guava (*Psidium guajava*), custard apple (*Annona squamosa*), pineapple (*Ananas comosus*), and jackfruit (*Artocarpus* spp.) are the major components of some tropical homegardens.

Nair and Sreedharan (1986) and Kumar and Kunhamu (2011) gave the inventory of crops and trees in homegardens of Kerala. Dagar (1995) and Dagar et al. (2014a) enumerated the yield of fruits and vegetables grown in the homegardens of coastal and island regions. In spite of very small average size of the management units, homegardens are characterized by high species diversity and usually 3–4 vertical canopy strata. A dynamic equilibrium can be expected with respect to organic matter and plant nutrients on the garden floor due to leaf litter and its constant decomposition. The energy and nutrient requirement of local people is fulfilled mainly through the products of these gardens. Another important aspect of these gardens is that the production for home consumption occurs throughout the year. The physical limitations such as remoteness of the area force the inhabitants to produce their basic needs by themselves. Unfortunately, there have been no serious efforts to provide the institutional and policy support for strengthening research on these traditional systems of exception merits.

Homegardens are traditional agroforestry system in Vietnam. In a piece of land around the house (0.5–5 ha), the land is used efficiently and effectively for growing fruits, vegetables, root crops, fish, livestock, fodder, fiber, medicine, small timber, fuel wood, and other products in multilayered structure. Most common homegardens have fruit trees, fishponds, livestock, and forest trees in an integrated system. Medicinal plants are also integrated. In delta homegardens, the main dominance is of fruit trees with three-storey canopy structure. Durian (*Durio zibethinus*), mango, and jackfruit form top storey; mangosteen (*Garcinia mangostana*), guava, lemon, *Achras zapota*, *Annona muricata*, *Citrus sinensis*, *Lansium domesticum*, banana, papaya, *Citrus reticulata*, and *Phyllanthus acidus* form middle storey, while ground storey is consisted of mainly vegetable crops, pineapple, forage grasses, etc. These homegardens have well-developed irrigation and drainage systems. On canal banks, *Cocos nucifera*, *Colocasia esculenta*, and *Alocasia odora* are planted. *Sesbania grandiflora* is planted as fence, green manure, and fuel wood. Some gardens also have flowers particularly *Rosa indica*, *Polianthes tuberosa*, *Dahlia pinnata*, and *Gladiolus gandavensis*. In the mid-hill homegardens on uplands (size 1.5–2.0 ha) depending upon slope and soil depth and knowledge and needs of farmers, tree species are arranged spatially and temporally. On hill tops, *Manglietia glauca*, coconut palm, and bamboos are commonly grown, while on slopes on terraced fields, various trees and crops form different combinations, viz., *Manglietia glauca* + tea (*Thea chinensis*) + *Tephrosia purpurea* + *Tephrosia candida*, *Cinnamomum cassia* + Cassava (*Manihot esculenta*) + *Cassia glauca*, *Aleurites fordi* + tea + pineapple + *Tephrosia purpurea*, and *Artocarpus integrifolia* + tea + pineapple are common. On foot hills, fruit trees such as jackfruit, longon, litchi, apricot, plum, banana, and persimmon are planted around houses; and local vegetables, viz., beans, cucurbits, spices, and medicinal plants, are grown under trees. Apiculture is also practiced besides trees. Lowest ground is used for rice field and fishpond. On terraced fields cassava and maize are intensively grown. These systems are economically viable and environmentally sound, ensuring soil erosion control and sustainable land use.

Okafor and Fernandes (1987) reported compound farms in southeastern Nigeria (West Africa) having trees of various heights forming multi-strata canopy of forest and fruit trees such as *Treculia africana*, *Dacryodes edulis*, and *Pterocarpus* sp. Products from crops such as yams, tubers, and other food crops and animals are consumed at home, and fruits and timbers are sold in the market. In general family labor is used and almost no chemical fertilizers are used. Using traditional knowledge and scientific technologies, there is enough scope of improving the systems. 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 in second storey; and food crops, fodder, cardamom, and medicinal herbs 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 recent years, much of the forested and bare lands are allocated to farmers where they grow trees along with their crops. Very well designed farming systems and their components have however been adopted by the farmers to improve the land capability. Tropical homegardens are essentially a complex integration of diverse vegetation where trees with understorey crops perform several production and service functions like livelihood (food, spices, fruits, vegetables, cash products), environmental benefits (biodiversity, shade, carbon sequestration, soil protection, nitrogen fixation, etc.), and cultural functions (conservation, utilization, recreation, traditions). Conservation of biodiversity, nutritional security of the family, strengthening of household economy, and improvement of soil health are the main attributes of the homegardens. Singh et al. (2014) have explained in detail some interesting observations on Angami and Konyak homegardens of Nagaland, Ingkhol homegardens of Manipur, and homegardens of War Khasi tribes of Meghalaya and Chktuah of Mizorum, which are economically and environmentally sustainable. There is a need of SWOT analysis of most of the homegardens so that further research for improving these may be planned. Dagar (1995), Kumar and Nair (2006), Pandey et al. (2007), Kumar and Kunhamu (2011), Kumar et al. (2012), Dagar et al. (2014a), and Dagar and Tewari (2016b) have given comprehensive account of homegardens including improved ones.

4.1.5 Plantation-Based Cropping Systems/Commercial Agroforestry

Modern commercial plantation crops like rubber (*Hevea brasiliensis*), coffee (*Coffea arabica/robusta*), and oil palm (*Elaeis guineensis*) represent a well-managed and profitable stable land use activity in the tropics. The scope for integrative practices involving plant associations in these commercial plantations is limited, except during the early phases of plantation when some intercropping is feasible, the commercial production of these crops is aimed at single-commodity objective. Some of the plantation crops like coconut palm have been cultivated since very early time but their economic yield remained low for a long time.

Contrary to popular belief, a substantial proportion of tropical plantation crops are grown by smallholders. For example, most of the cacao production in Ghana and Nigeria comes from smallholdings where it is grown with specific crops like maize (*Zea mays*), cassava (*Manihot esculenta*), banana, cucumber (*Cucumis* spp.), and sweet potato (*Ipomoea batatas*) especially during the first 4 years of planting cacao. In Trinidad, it is grown under forest shade trees. In Kenya, the crop land is characterized by the upper layer being dominated by tall trees such as *Cordia africana*, *Grevillea robusta*, *Commiphora zimmermannii*, and *Trema orientalis* and the middle layer by shrubs (banana and fodder shrubs), while the ground layer is dominated by the annual crops (maize, beans, root crops) and grasses. Cut-and-carry system assures that there is no damage by animals. Inhabitants of the highlands in Kilimanjaro in Tanzania have Kihamba or Chagga homegardens usually having four vegetation layers (Hemp and Hemp 2008). Apart from some cultivated fruit trees (avocado, mango) and some introduced timber trees (*Grevillea robusta*, *Cupressus lusitanic*a), there are more than 80 tree species which are encountered in these plantations. Most widespread are *Albizia schimperiana*, *Rauvolfia caffra*, *Cordia africana*, *Commiphora eminii*, and *Margaritaria discoidea*. Some of these cover banana and coffee fields and also cocoyam (*Colocasia esculenta*). Species such as *Dracaena fragrans* are planted as hedge. Some epiphytes such as fern *Drynaria volkensii* and *Telfairia pedata* (a liana with oil containing seeds) find place on *Albizia schimperiana* var. a*manuensis*. Under banana and coffee, farmers grow vegetables and sometimes fodder grasses for livestock rearing.

In the vast Amazonian humid tropical lowland region of South America (Brazil, Peru, Colombia, Venezuela, Guyana, etc.), many tall timber trees associated with fruit trees and various palms form typical Amazonian plantation-based system in which cacao, Brazil nut (*Bertholletia excelsa*), agricultural crops, cassava, yams, beans, plantain, etc. are commonly cultivated (Miller and Nair 2006). Fruit trees along with other trees are also planted around houses. Indigenous knowledge of interaction of plants and environment as well as social systems helps in domestication of indigenous species.

Many smallholder rubber plantations in Southeast Asia and Nigeria are based on integrated crops including soybean, maize, banana, groundnut, fruit trees, coconut, and black pepper. In Malaysia poultry raising in rubber stand is a common wealth. In Nicobar Islands (India) poultry and domestication of pigs with coconut is very old practice. Most of the coconut production in India, the Philippines, Sri Lanka, and the Pacific Islands comes from small holdings in which coconut palm is integrated with a large number of annual and perennial crops like clove (*Syzygium aromaticum)*, cinnamon (*Cinnamomum zeylanicum*), coffee, cacao, cassava, yams (*Dioscorea alata*), fodder grasses, and legumes. Grazing under coconut and cashew nut (*Anacardium occidentale*) is also common. In India, Tanzania, Mozambique, and Senegal, smallholders grow cashew nut commonly (in wider spaces) with other crops. Coffee is integrated with other crops like banana and maize in Ethiopian highlands, Colombia, and Kenya. Coconut is one of the most widely grown tree crops in the tropics mostly on islands, peninsulas, and along coasts, covering an area of six million ha (Nair 1993). The major coconut-producing countries are the Philippines, Indonesia, India, Sri Lanka, Malaysia, and the Pacific Islands, and the most of the production is from small holdings.

Important food crops grown with coconut include cereals (rice, finger millet, and maize); pulses (pigeon pea, green and black gram, coupe, soybean, groundnut); root crops (sweet potato, yams, cowpea, elephant foot yam, and taro); spices and condiments (ginger, turmeric, cinnamon, clove, chilies, and black pepper and fruits like pineapple, mango, banana, papaya, and bread fruit); other crops (cotton, sugarcane, sesame, abaca, and vegetables); tree crops (areca nut, cacao, and coffee); improved pasture grass species of *Brachiaria*, *Dichanthium*, *Panicum*, *Setaria*, *Paspalum*, and *Pennisetum*; and improved forage legumes of *Stylosanthes*, *Desmodium*, *Glycine*, *Leucaena*, and *Macroptilium*. Many trees such as species of *Erythrina*, *Ficus*, *Tamarindus*, *Gliricidia*, *Ceiba*, and *Cordia* find the place in these systems. Dagar (1995), Dagar et al. (2014a), and Dagar and Tewari (2016b) gave detailed account of plantation-based agroforestry in coastal and island regions.

Domestication of large cardamom (*Amomum subulatum*) plantations under *Alder* (*Alnus nepalensis)* in Northeastern Himalayan Region and its collection from the natural forests by indigenous Lepcha and Limbu tribes is an age-old agroforestry practice. Besides *Alnus nepalensis*, there are 29 other tree species, supporting this plantation crop. Tree management practices by farmers involve harvesting trees above 16 cm basal diameter to assist natural regeneration of younger tree seedlings and open canopy to regulate light at the ground. This tree management system provides continuous supply of fodder and fuel wood. The nitrogen- fixing trees help site improvement and better growth of cardamom. The tree management helps cardamom production also. With other fodder trees, lopping during November after maturation of cardamom and not allowing twigs to fall on it does not interfere with the production and makes it an economically viable system. Singh et al. (1982) and Prasad and Singh (1994) have made extensive study on cultivation of large cardamom with *Alnus nepalensis* tree in eastern Himalaya region. Sharma et al. (2000, 2009) reported that the yield of finished cardamom under Alder (454 kg ha^{-1} yr^{-1}) was almost double than produced under natural forest canopy (205 kg ha^{-1} yr^{-1}). This system has the potential to generate net income of INR 80,000–90,000 (US$ 2192) per ha per annum. *Albizia chinensis*, *A. lebbeck*, *A. procera*, *Anogeissus acuminata*, *Bauhinia variegata*, *Ficus* spp., *Gmelina arborea*, *Kydia calycina*, *Mesua ferrea*, *Moringa oleifera*, *Parkia roxburghii*, *Pinus kesia*, *Quercus* spp., *Schima wallichii*, *Bambusa* spp., *Dendrocalamus* spp., *Artocarpus heterophyllus*, *Michelia oblonga*, *Parkia roxburghii*, *Prunus cerasoides*, and *Symingtonia populnea* are other commonly cultivated multipurpose trees in these regions. Mango (*Mangifera indica*), guava (*Psidium guajava*), mandarin (*Citrus* spp.), and banana (*Musa paradisiaca*) are common fruit trees. Turmeric (*Curcuma domestica*), ginger (*Zingiber officinale*), taro (*Colocasia esculenta*), pineapple (*Ananas comosus*), groundnut (*Arachis hypogaea*), soya bean (*Glycine max*), and vegetables are common intercrops grown with fruit trees and multipurpose trees (for more details, see Singh et al. 2014).

4.1.6 Scattered Multipurpose Trees on Farmlands

The practice of growing agricultural crops under scattered trees on farmlands is quite old and seems to have scarcely changed for centuries. Though the worldwide list of such trees is long, some of them have received more attention compared to others, for example, *Prosopis cineraria* in northwestern India and *Faidherbia albida* in West Africa. In arid regions, this is the most prevalent system particularly on grazing lands. Tewari et al. (2014) gave a comprehensive account for hot desert ecology. The species diversity in these systems is very much related to ecological conditions. With the increase in rainfall, the species diversity and system complexity increases. Thus, we find a proliferation of more diverse multistoreyed homegardens in the humid areas and less diverse, two-tiered canopy of configurations (trees + crop) in drier areas. Pathak and Dagar (2000) compared prevalent agroforestry systems in various ecological zones and found that the number of plant species per unit area, canopy layers, and the animal species dependent upon them show greater richness in tropical ecological zones than in arid or subtropical zones.

In China, during dynasty rule (206 BC–AD 220) raising of forests was recommended along with livestock and crops as per different site conditions. Utilization of competitive habit of fast-growing species for tree production is very old in China. For example, Chinese Scholar tree (*Sophora japonica*) and *Broussonetia papyrifera* raised with sun hemp (*Crotalaria juncea*) and soybean (*Glycine max*) with Chinese chestnut (*Castanea* sp.) are described in sixth-century Chinese books (Xiuling 1995). Ancient agriculture books in China (sixth-century literature) also insisted that tea (*Thea chinensis*) must be sown under mulberry (*Morus alba*) or bamboo because it was afraid of direct light. Similarly, mulberry may be interplanted with several crops. Proso millet (*Panicum miliaceum*) grown under mulberry could promote the growth of both species, but foxtail millet (*Setaria italica*) will have negative effect on mulberry and promoted growth of harmful insects. Sorghum was not desired because it grew to same height as mulberry, resulting in each shading the other from the sun. Other trees such as *Sapium setigerum* could not be utilized for interplanting because of their serious shading characters.

In ancient India, trees were given more importance than crops in tree-crop mixed cropping. Today also the trees are found grown scattered in agricultural fields for many uses such as shade, fodder, fuel wood, fruit, small timber, vegetables, and medicinal uses. Some of the practices are very extensive and highly developed. For example, growing of *Prosopis cineraria* and *Ziziphus nummularia* in arid areas; *Dalbergia sissoo*, *Acacia nilotica*, *Syzygium jambos*, *S. cumini*, *Morus alba*, and *Mangifera indica* in Indo-Gangetic plains; *Grewia optiva*, *Quercas* spp., and other tree species in the Himachal Pradesh; *Ficus benghalensis* in Karnataka; *Acacia leucophloea* and *Tamarindus indica* in Tamil Nadu and Andhra Pradesh; *Eucalyptus globulus* in the southern hills of Tamil Nadu; and *Borassus flabellifer* in peninsular coastal regions on fields along with crops is very common (Dhanya et al. 2014; Dagar et al. 2014a; Dagar and Tewari 2016b). These, along with many others, are also common on pasture lands and their leaves are also harvested for animal fodder. Kessler (1992) reported that approximately 20 different tree species are common in the parklands (savannas) in the Sahelian and Sudanian zones of Africa. Nair and Dagar (1991) and Dagar et al. (2014b) documented a profile of numerous tree species found growing in different agroclimatic regions of India. There are strong convictions for the acceptance of these trees on agricultural fields since time immemorial. The very fact that Khejri (*Prosopis cineraria*) is omnipresent in dry regions and its occurrence is encouraged in all the cultivated fields and village grazing grounds shows that its usefulness is generally and widely accepted by land owners who have a strong conviction that the tree does not hinder crop productivity in the adjoining areas. Moreover, studies conducted have shown that the soil under *P. cineraria* has more organic matter, total nitrogen, total phosphorus, total potassium, available phosphorus, and potassium and micronutrients (Zn, Mn, Cu, and Fe) and slightly lower pH and electrical conductivity than the soil under field conditions without trees (Aggarwal 1980; Shankarnarayan et al. 1987; Tewari and Singh 2006). Similarly, *Ziziphus nummularia* is preferred and is a favorite bush in Rajasthan. Studies have shown that in hilly areas the yields of wheat and paddy decreased consistently when *Grewia optiva*, *Morus alba*, and *Eucalyptus tereticornis* were grown over a period of 13 years, and growing of crops alone was found more economical (Khybri et al. 1992). But the variety of products obtained was more when trees were grown with crops. More details are given by Kashyap et al. (2014).

However, in the foot hills of Shivaliks, Grewal (1992) reported that growing Bhabar grass (*Eulaliopsis binata*) with *Eucalyptus* and *Acacia catechu* is highly economical. Farmers retain trees of *Acacia nilotica*, *A. catechu*, *Azadirachta indica*, *Butea monosperma*, *Dalbergia sissoo*, *Mangifera indica*, and *Ziziphus mauritiana.* Trees such as *Gmelina arborea* and *Salvadora persica* are preferred in Gujarat with crops. Farmers in subhumid *terai* region of Indo-Gangetic plains prefer *Dalbergia sissoo*, *Psidium guajava*, *Mangifera indica*, *Morus alba*, *Syzyzium cumini*, and *Grewia nudiflora*. In Bihar, *D. sissoo*, *D. latifolia*, *Litchi chinensis*, and *Mangifera indica* are frequently grown on fields. Farmers in northeastern region prefer *Alnus nepalensis*, *Artocarpus chaplasha*, and species of *Bambusa*, *Dendrocalamus*, and fruit trees like *Mangifera indica*, *Emblica officinalis*, and *Parkia roxburghii*. In coastal areas of peninsular India, *Borrasus flabellifer* is found scattered in the fields of groundnut, rice, and green gram. Every part of the palm is used by common man. The leaves for thatching, trunk as pillar or timber, fruits are consumed roasted and the radicles of germinating seeds are eaten roasted, and a beverage (alcohol) is extracted from the spadix which is also used to prepare jaggery and vinegar. Other most common trees found on farmers' fields are *Azadirachta indica*, *Moringa oleifera*, *Tamarindus indica*, *Ceiba pentandra*, *Anacardium occidentale*, *Cocos nucifera* palm, and fruits like banana, custard apple, guava, and pomegranate.

In Nepal, growing fodder trees on the terrace risers is very common. This provides fodder to the animals while protecting the farmland from terrace failure (Joshy 1997). The bamboo is also planted for erosion control and people use the bamboo poles as wall to project terraced rice fields. In some places they also use *Alnus nepalensis* and quick-growing species, and forest litter is collected from the high hills and after partially decomposing. It is incorporated in the fields serving as compost.

The Quezungual system from western Honduras in North America is almost similar to indigenous system followed by small landholders. Most of the regenerating trees are retained and pollarded to a height of about 1.5 m. Farmers also retain tall trees such as *Cordia alliodora*, *Diphysa robinioides*, and various fruit trees such as *Byrsonima crassifolia*, *Mangifera indica*, *Persea americana* (advocado), *Carica papaya*, *Anacardium occidentale*, and *Psidium guajava* along with annual crops such as maize (*Zea mays*), sorghum (*Sorghum bicolor*), and beans (*Phaseolus vulgaris*). Some of these fruit trees are planted and an optimum shade is assured (Hellin et al. 1999). In African countries like Kenya, there is fairly good awareness about agroforestry, and people retain trees like *Faidherbia albida*, *Cordia africana*, *Dombeya goatzinii*, *Grevillea robusta*, and *Commiphora zimmermannii.*

Undoubtedly, the multipurpose trees, whether on farms or on pasture lands, are the most important component of all agroforestry systems, but very little efforts have been made to improve these for higher production.

4.1.7 Trees on Farm Boundaries

Trees that are grown in agricultural fields or on field bunds are also often and usually grown on farm boundaries. This is almost common throughout the world. The difference lies only in composition of species and the purpose. Most of the time, these are local species and used as live fences. In northern parts of India particularly in Haryana and Punjab, both *Eucalyptus* and *Populus* are commonly grown along field boundaries or bunds of paddy fields. Other trees which are found grown as boundary plantations or live hedge include *Acacia nilotica*, *Dalbergia sissoo*, *Morus alba*, *Syzygium cumini*, *S. jambos*, and *Azadirachta indica*. Farmers of Sikkim grow bamboo (*Dendrocalamus*) all along irrigation channels. In coastal areas of Andhra Pradesh, *Borassus* is most frequent palm. In coastal and island regions, farmers grow *Gliricidia sepium*, *Jatropha* curcas, *Ficus* sp., *Ceiba pentandra*, *Vitex trifoliata*, *V. negundo*, and *Erythrina indica* as live hedges. At many places succulents like *Agave* and many cactoids are grown as common live fence.

The boundary plantations also help as shelterbelts and wind breaks, particularly, in fruit orchards. In Bihar, *Dalbergia sissoo* and *Wendlandia exserta* are most common plantations. *Casuarina equisetifolia* and *Acacia auriculiformis* are extensively planted on field bunds and along sandy coastal areas in Orissa. Pathak et al. (2014) and Korwar et al. (2014) have also dealt in detail the plantations on bunds for rainfed areas and Indo-Gangetic plains of India.

4.1.8 Woodlots

In many parts of the world, farmers grow trees in separate block as woodlot along with agricultural fields. This practice is expanding fast due to shortage of fuel wood and demand of poles or pulpwood in industry. For example, bamboo poles are in great demand for orange orchards in Nagpur district and *Eucalyptus* and *Populus* for WIMCO industries in India. The woodlots are being raised mostly on large farms due to the increase of labor costs and labor management, lack of irrigation, and risk of crop investments. Woodlots of casuarina, bamboo, poplar (*Populus deltoides*), eucalyptus, red sanders (*Pterocarpus santalinus*), *Dalbergia sissoo*, etc. have become popular in many parts of India. While comparing traditional indigenous trees on the farmland with commercial *Eucalyptus* plantation, Shiva et al. (1985) observed that the traditional trees had a multiplier effect in all the activities of household promoting rural industries and employment while the *Eucalyptus* had limited scope.

In Europe also, woodlots of forest tree species and tree intercropping and forest farming with ginseng (*Panax quinquefolius*) and other cash crops, riparian woody buffers, and collection of non-timber forest products are traditional practices particularly in Canada (Thevathasan et al. 2012).

4.1.9 Shelter Belts

Arid regions witness very high wind velocity throughout the year, and sand can initiate movement of particles even at 12–14 km hr^{-1} wind velocity. Farmers build kinds of obstacles to stop sand movements called *kana bandi* (e.g., in Rajasthan) either by using pieces of small dead wood or local vegetation to check wind velocity within safer limits (Mathur 1995). *Crotalaria burhia*, *Leptadenia pyrotechnica*, and Ae*rva psuedotomentosa* are planted in 20–25 m apart in rows across the wind direction. Between the lines of these shrubs, grasses, viz., *Cenchrus ciliaris*, *C. setigerus*, and *Lasiurus scindicus*, are planted on leeward side of each break. This permanent vegetation helps accumulating sand near them which is again spread in the field. This also helps increased crop yields along the lines. Due to overexploitation for multiple uses, shrubs such as *Phog* (*Calligonum polygonoides*) once predominant on sand dunes have become endangered. *Balsamodendron berryi* is a traditional silvopasture protecting live hedge, particularly in dry regions of Andhra Pradesh. Other common hedge species include *Gliricidia sepium*, *Jatropha curcas*, *J. gossypifolium*, *Lantana camara*, *Agave sisalana*, *Prosopis juliflora*, *Balanites roxburghii*, *Pithecellobium dulce*, *Parkinsonia aculeata*, *Lawsonia inermis*, *Carissa carandas*, *Vitex negundo*, *V. trifoliata*, and many cactoides. *Hippophae rhamnoides*, earlier considered to be brush wood and has emerged as commercial crop because of its fruits, is very common boundary plantation in cold desert area in Leh.

In Europe hedgerows and windbreaks are important traditional systems particularly in the Atlantic region and Central Europe. The primary role of windbreaks is prevention of wind erosion, but also they offer shade for grazing animals, maintain a uniform snow cover, and provide fuel wood. The lumber hedgerows provide live fences to prevent animals from mixing with neighboring herds.

4.1.10 Trees on Rangelands

In Europe wood pastures are reported to be practiced from Neolithic times (6000 BP) and can be found all over Europe. In this system, cattle are allowed to graze in the forest. Some systems, e.g., Dehesa (in Spain) and Montado (in Portugal), are very old grazing-based systems (4500 years old) found in the Mediterranean zone, characterized by the presence of savannah-like open tree layer, mainly dominated by evergreen oaks and grasses. Traditional systems were highly diversified in terms of livestock types (sheep, goats, pigs, cattle, horse). Pollarding and *pannage* practices are also common in Central Europe, where branches from trees are cut to provide leaf fodder for livestock and produce wood for fuel. Pannage is the specific name for pig grazing in beech (*Fagus* spp.) and oak (*Quercus* spp.) woodlands (Nerlich et al. 2013). In many Europian countries, various temperate fruit-and-nut trees such as apple, plum, pear, peaches, walnut, almond, sweet chestnut, and figs are dispersed on meadows and pastures in irregular pattern (Herzog 1998). These stands are common refuge for small mammals, nesting for birds, apiculture, and pleasant landscapes. The Chania system of Greece and other parts of southeastern Europe is a traditional widespread practice since first millennium BC and popular even now. Cereals are intercropped with fruit trees, olives, sweet chestnut, and walnut and are also grown on pastures involving cattle and goats. Leaf and twigs cut from trees and hay from intercropped cereals help livestock survive during winter (Papanastasis et al. 2009). The systems are a part of traditional way of life and rich cultural history.

In dry regions of Indian subcontinent, tree species such as *Salvadora oleoides*, *S. persica*, *Capparis decidua*, *Acacia nilotica*, *A. senegal*, *A. leucophloea*, *Prosopis cineraria*, *Ziziphus nummularia*, *Balanites roxburghii*, *Dichrostachys cinerea*, and now *Prosopis juliflora* are most frequent on community grazing lands. Invasion of *P. juliflora* suppresses other species on grazing lands. In coastal areas, coconut is the most common tree on pasture lands. Cattle raising usually involve grazing on these pastures. In some areas, special fodder plant species particularly legumes, are cultivated. The research results in Sri Lanka have indicated that, as with the case of intercropping, the pasture will not diminish the yield of palm if fertilizers are applied to both (c.f. Nair 1993). An organized form of this natural vegetation as silvopasture assures 10 Mg ha^{-1} yr^{-1} biomass production (as against 1 Mg ha^{-1} yr^{-1} from natural stands) at 10-year rotation in dry zones besides assuring soil conservation, healthy environment, and employment generation (Pathak et al. 1995). While explaining the nature of grassland dynamics and their management, Dagar and Pathak (2005) and Pathak and Dagar (2015) have cited several examples of trees playing crucial role in management of grazing lands. Based on long-term studies, Rai (2012) has reported the role of *Ailanthus excelsa*, *Acacia tortilis*, *Hardwickia binata*, and *Leucaena leucocephala*-based silvopastoral systems for livestock production in detail.

In Austalia, pastures are one of many means of obtaining productive use and rehabilitation of waterlogged saline soils. These pastures include salt-tolerant fodder shrubs (species of *Atriplex*, *Halosarcia*, and *Maireana*), perennial grasses (*Puccinellia ciliata*, *Thinopyrum ponticum*, *Distichlis spicata*, *Paspalum vaginatum*, *Sporobolus virginicus*, *Pennisetum clandestinum*, *Chloris gayana*, etc.) and some annual species. Barrett-Lennard (2003) gave extensive account of pasture lands in Australia. Some of the most useful species for Australian salt-affected soils were introduced from overseas and performed well, and those include *Puccinellia ciliata* and *Thinopyrum ponticum* (tall wheatgrass) from Turkey, *Atriplex undulata* (wavy leaf saltbush from Argentina, and *Atriplex lentiformis* (quail bush) and *Distichlis spicata* from the United States. Somarriba (1992) explained “protein bank” concept as a form of silvopastoral practice in which trees and shrubs (mostly leguminous fodders) are planted in and around the farmland and rangelands. Usually the foliage of these trees is cut-and-carried for feeding animals kept in control conditions or sometimes animals are fed on these on regular intervals. Often these species (e.g., *Prosopis cineraria*, *Acacia nilotica*, *Feronia limonia*, *Ziziphus nummularia*, *Balanites roxburghii*, *Leucaena leucocephala*, etc.) are highly nutritive and sprout easily. There are conclusive evidences to suggest that improved silvopastoral systems with suitable tree species and their management practices such as lopping, fertilizer applications, germplasm improvement, introduction of legumes, etc. has a lot of scope to improve the productivity of existing pasture lands. There is also great potential to utilize sylvopastoral systems in drylands to solve problems like global warming (through increased carbon sequestration) and for biodiversity conservation (Soni et al. 2016). The value-added products from silvopastoral systems, particularly from animal component, have ample scope to improve the livelihood of farmers in dry region. Recently, Peri et al. (2016) have compiled a comprehensive account of silvopastoral systems in southern South America.

4.1.11 Other Systems

Throughout the coastal regions aqua-forestry is quite common, where farmers are cultivating fish and prawn in saline water along rice and also in ponds. They grow coconut and other trees on bunds of ponds. These trees help in producing litter to feed fishery and generating extra income to the farmer. Now fish culture in association of mangroves is also advocated which are rich sources of nutrition to the aquatic life and breeding ground for juvenile fish, prawn, and muscles (Dagar 1995; Dagar et al. 2014a). Backyard poultry is another adventure in many coastal regions. A well-balanced system of animal husbandry including goats, cattle (sometimes rabbit), poultry, ducks, turtles, and fish in the small ponds in homegardens makes a balanced system of high moisture, energy, and nutrient use efficiency per unit area. The leaves of many trees such as *Gliricidia sepium*, *Leucaena leucocephala*, and *Moringa oleifera* have been found to serve as fish - feed when offered as pallets and improved the productivity of fishpond. In many parts of India, farmers are raising forest and fruit trees on the dykes of fishponds on their farms and are generating good income.

5 Agroforestry Research Developments During Last Three Decades: Agroforestry Coming of Age as Science

During last three decades, agroforestry research has come of an age. 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, a nearly one billion hectares of agricultural landscapes now have trees on them (Garrity 2012). 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. During the 1990s, thanks to agroforestry, about 38% of the countries experienced increase in forest cover, particularly in Europe, North America, and East and South Asia. Many traditional and indigenous systems have been improved through research inputs and techniques have been developed to handle the problematic areas. For example, many improved short fallows, improved pastures, and modern homegardens have been developed inculcating the indigenous knowledge while developing present-day technologies. Farmers are gaining good economic returns from improved homegardens as well as improved fallows and pastures.

As discussed earlier, "improved short fallows" of African countries such as Eastern Zambia, Zimbabwe, South Cameroon, and Ghana; woodlots of Tanzania and many European countries; enrichment of traditional cultivation of Eastern Amazonia; integrated farming systems involving trees, fruits, crops, fishery, livestock, poultary, apiculture, and mashroom culture (all or a few components) on the same unit of land in India; site-specific problem-solving agroforestry systems; and alley cropping systems across the world are the examples of progress made in agroforestry research during the past three decades. 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. Sand dunes have been stabilized in many arid regions using appropriate technologies. Agroforestry is being extended as a tool for solving many environmental and social problems even in the developed countries. Results of some of the recent research (during last three decades) efforts have been summarized below.

5.1 Evaluation of Multipurpose Trees and Development of Improved Agroforestry Systems

In early stages of agroforestry research, one of the major agendas was to collect, identify, and evaluate multipurpose tree species (MPTs) for their suitability in an ecological zone. Major emphasis had been on nitrogen-fixing tree species. A few genera such as *Acacia*, *Calliandra*, *Casuarina*, *Gliricidia*, *Leucaena*, *Prosopis*, and *Sesbania* figured prominently in tropical agroforestry systems. The collection and evaluation of MPTs resulted in establishment of arboretum in many agroforestry centers across the world. For example, a collection of 184 species was made followed by identification of priority tree species of agroforestry research for various agroclimatic conditions by different agroforestry centers working under the All India Coordinated Research Project (AICRP) of Agroforestry in India, and ICRAF also facilitated the distribution of germplasm of improved species in different agroecological regions across the world (www. nrcaf.org; www.icraf.org). Provinance trials of at least two species identified by each AICRP situated in a specified agroclimatic zone were conducted after collecting germplasm from different locations in the country. A significant contribution of the project was on tree selection and improvement of species of different genera such as *Acacia*, *Ailanthus*, *Azadirachta*, *Casuarina*, *Dalbergia*, *Eucalyptus*, *Leucaena*, *Mangium*, *Melia*, *Moringa*, *Pongamia*, *Prosopis*, and *Ziziphus*. Some nongovernmental organizations (NGOs) have also contributed to a greater extant for developing fast-growing clones of *Eucalyptus*, *Casuarina*, *Dalbergia*, and *Melia* which has brought a sea change in adaptability of agroforestry in the country. The implementation projects are in operation, for example, in Haryana clonal *Eucalyptus* has been planted either on acreline as boundary plantation of agricultural fields or in farm forestry mode, planting trees in wider spaces to adjust about one thousand plants per ha and growing arable crops as intercrops in waterlogged areas to bring down the water table and improve the land for cultivation (Dagar et al. 2016a). This has not only helped farmers to reclaim waterlogged land but has also increased the income of the farmers and sequestered carbon.

Under National Agricultural Technology Project, an "Agroforestry BASE" online database has been developed which is being updated periodically by Central Agroforestry Research Institute (CAFRI), Jhansi, India. Agronomic practices such as planting methods, irrigation methods, composition and fertilization, and spacing and pruning schedules for raising some of the promising MPTs in association with annual crops have been developed and standardized. Crops and cropping sequences which can be grown successfully (without significant reduction in yield through agronomic manipulations and tree canopy management practices) in association with forest and fruit trees have been identified.

Many agroforestry systems are addressed by the major constitute species. For example, *Morus alba* and *Grewia optiva*-based agroforestry systems for western Himalayas, Alder (*Alnus nepalensis*)-based system for northeastern Hill region, *Eucalyptus tereticornis* (mostly clonal) and *Populus deltoides*-based systems for Indo-Gangetic region, Aonla (*Emblica officinalis*) and Khejri (*Prosopis cineraria*)-based systems for semiarid and arid regions, Teak (*Tectona grandis*)-based system for tropical region, and *Gmelina arborea* and *Acacia leucophloea*-based systems for humid and subhumid regions have been developed. The AICRP on agroforestry initiated systematic work on biofuel research with major emphasis on *Jatropha* and *Pongamia*. *Simarouba glauca* has also recently come in limelight.

A network project on bamboo-based agroforestry systems has also been initiated at six centers. Keeping in view the present-day challenges, the project is now focusing on the role of agroforestry in meeting the environmental challenges, value addition for creating livelihood opportunities, and application of modern tools and technologies in agroforestry research. A distinct feature of agroforestry land use system is to utilize woody perennials (including fruit trees and palms) for production as well as conservation. Atul et al. (1994), Tomar et al. (2012), and Kashyap et al. (2014) have reported the production potential of traditional agroforestry system in mid-hills of Himachal Himalayas, Pathak et al. (2014) in Indo-Gangetic plains, Tewari et al. (1998) and Tewari and Singh (2000) in hot arid regions of Rajasthan, Korwar et al. (2014) and Tewari et al. (2014) in rainfed dry areas, and Dagar et al. (2014a) in coastal humid regions. The prevalent systems and their species components have been compiled by many workers (Pathak and Dagar 2000; Dagar et al. 2014b; Dagar and Minhas 2016; Dagar and Tewari 2016a).

5.2 Temperate Agroforestry Systems

In Europe and the United States, agroforestry has been practiced since ancient times, but science-based agroforestry research gained attention only recently. The realization that agroforestry systems are well suited for diversifying farm income while providing environmental services and ecosystem benefits has increased receptivity on the part of some landowners in these regions. Jose et al. (2012) have found that agroforestry systems in the United States offer great promise to produce biomass for biofuel, specialty in organic crops, and pasture-based dairy and beef and also offer proven strategies for carbon sequestration and climate mitigation, soil enrichment, biodiversity conservation, and air and water quality improvement. The USDA Agroforestry Strategy Framework released in 2011, identified agroforestry as an important component of a much-needed national strategy to enhance agricultural landscapes, watersheds, and rural communities. The five categories of agroforestry practices in temperate regions especially in the United States and Europe include riparian and upland buffers (ameliorate nonpoint source pollution, abate soil erosion and nutrient loading, protect watersheds), wind breaks, alley cropping, silvopasture, improved fallows, and forest farming. Marginal floodplain land is considered ideal for biomass production using agroforestry model. Such lands could be placed into an alley cropping or in riparian buffer system that would integrate rows of short rotation, high-yielding woody crops such as willow (*Salix* spp.), and poplar (*Populus* spp.) with alleys of perennial grasses (Jose et al. 2012).

Based on their analysis, Udawatta and Jose (2011) concluded that silvopastoral systems, the most common practice in North America, had the greatest potential to sequester C in the United States. Using a sequestration potential of 6.1 Mg ha^{-1} year^{-1} on 10% marginal land (23.7 million ha) and 54 million ha of forests, they estimated total C sequestration potential for silvopastoral land in the United States as 474 Tg C year^{-1}; and alley cropping (practiced on 10% of 179 million ha cropland) could sequester 60.9 Tg C year^{-1}.

In Canada, the riparian buffer systems are promoted for the Atlantic region; tree-based intercropping and windbreak systems in Quebec, Ontario, and the Prairies; and silvopastoral system in British Columbia. Additionally, windbreaks have a special value in blueberry (*Vaccinium corymbosum*) production system. At the St-Edouard site, N_2O emissions were found to be three times higher in monocropped plots as compared to agroforestry plots (Beaudette et al. 2010) showing the potential of agroforestry in mitigating greenhouse gas emissions. A variety of individual enterprises and community initiatives incorporate forest farming elements into their business models in Canada. Developing cottage industries focused on paper birch (*Betula papyrifera*) and big-leaf maple (*Acer macrophyllum*) tapping, harvesting sap from the tree to make birch or maple syrup, is an ideal example.

Though traditional agroforestry systems in Europe are age-old, the current practices are based on a relatively narrow range of dominant tree species. Most of them are broad-leaved (74%) and are found in Mediterranean environments in silvopastoral systems; actually oaks (*Quercus*) are the predominant tree species. For example, in Spain, *Q. ilex* and *Q. suber*; in Greece, *Q. humilis*, *Q. frainetto*, *Q. coccifera*, and *Q. trojana*; and in Italy, *Q. cerris*, *Q. humilis*, and *Q. suber* are commonly found species. The coniferous species (*Pinus nigra*, *P. sylvestris*, *Juniperus communis*, *J. sabina*, *Abies cephalonica*) are found on high altitudes (Mosquera-Losada et al. 2012). By contrast, reindeer husbandry systems based on forest understorey resources in Finland, Norway, and Sweden extend to 33–40% of total area of these countries (Jernsletten and Klokov 2002). *Pinus sylvestris* occurs in most of the agroforestry systems in these regions. Papanastasis et al. (2009) described 40 prominent on agricultural and pastoral systems in Greece. Most common systems consist prominent tree species such as walnut (*Juglans regia*), almond (*Prunus dulcis*), mulberry (*Morus alba*), populus (*Populus nigra*), olive (*Olea europaea*), carob (*Ceratonia siliqua*), and fig (*Ficus carica*) associated with crops such as maize (*Zea mays*) and other cereals, vegetables, vines, forage crops mainly lucerne (*Medicago sativa*), and tobacco (*Nicotiana tabacum*). Those systems which involve cereals become agrisilvopastoral as animals graze on stubble after grain harvest. Parkland systems are also valued for their landscape, biodiversity, and cultural value. In modern agroforestry, fruit orchards and value-added wood products, and high-value mushroom (truffles) and medicinal and aromatic plants particularly cultivated in forests, are given due wattage.

Agroforestry in northwestern temperate Himalayan regions of India is a composite, diversified, and sustainable land use. Many traditional systems such as homesteads (*kyaroo*), plantation crop combinations, bamboo groves, and fruit-based silvopastoral systems are prevalent. Recently, sea buckthorn (*Hippophae rhamnoides*) system has gained importance because of multiple uses of the bush such as making fruit juices of commercial importance, medicinal value, and environmental benefits such as desert control and its adaptability to degraded habitats in cold regions. Based on research and experiences of farmers, many remunerative systems involving fruit and fodder trees, crops, and forages have been developed for different hill zones. In low hill regions *Kinnow* (*Citrus nobilis* × *C. deliciosa*)- or mango (*Mangifera indica*)-based cropping systems; *Populus deltoides* and *Eucalyptus*-based agri-silvicultural systems with commercial crops like zinger (*Zingiber officinale*) or turmeric (*Curcuma domestica*); multipurpose (mainly fodder) trees on *ghasnies* (pasture lands) on sloping lands with sufficient constituent of legume fodders; and sometimes block plantations are followed. Unlike traditional systems, farmers generate additional income from commercial products. Nowadays, medicinal and aromatic plants under high density peach plantations or poplar plantations on mid-hill zone form quite remunerative system. On high hill temperate zone, apple (*Malus pumila*)-based cropping systems (mainly vegetables, mustard, beans) not only offer diversification in different growing seasons but also help in generating high income without affecting the fruit yield of the orchard. In Kashmir Valley, forest and fruit tree-based pastoral models involving apple, almond (*Prunus amygdalus*), cherry (*P. avium*), and other nut trees; *Ulmus wallichiana* tree in alleys across slope; aromatic and medicinal plants including high-value *Salvia sclarea* (commercial aromatic herb producing linalool and linalyl acetate, main constituent of aromatic oil used in perfumery); temperate forage grasses; and legumes integrated with animals have been developed. Though recently enough research inputs have been added but still many of these systems need to be further improved with suitable technological interventions. In recent times, due to rise in average temperature, the apple belt has shifted toward higher altitudes increasing the total area under the apple. Impact of climate change on various agroforestyry systems including livestock behavior needs to develop new research programs. Recently, Kashyap et al. (2014) and Verma et al. (2016) have given extensive account of different agroforestry systems in northwestern Himalaya region and Tewari et al. (2016) for cold desert in Leh region.

Temperate agroforestry systems generally result in greater nutrient cycling than pure agricultural crops because the leached nutrients from the crop rhizosphere can be captured by the deeper roots of trees once the crops are not able to take them up due to excess of inputs or the lack of crop growth hence shallow roots (Lehmann 2001; Bambo et al. 2009). In turn, these nutrients are made available to crops through litter fall. Moreno et al. (2007) described how nitrogen, phosphorus, and other nutrients were increased near the trees in a Dehesa system. The importance of this better nutrient use and recycling is clear, and nutrients are not lost from the system which helps in checking contamination of watercourses. Nitrogen leaching in waterbodies can cause eutrophication problems in rivers and other water sources; therefore, agroforestry helps in reducing nitrogen leaching and contamination of underground water.

5.3 Systems for Environmental Benefits

The underlying concept of various ecosystem services of all agroforestry systems is the beneficial role of on-farm and off-farm tree production in providing numerous advantages and services besides livelihood products such as food, fodder, timber, fuel wood, fiber, medicine, etc. These services may include rehabilitation and improvement of degraded lands, biodiversity conservation, improvement of landscapes in urban and peri-urban areas, recreation, and general improvement in environment. All the life-supporting ecosystem functions provided by agroforestry systems including nutrient cycling, water quality enhancement, pollution control, and below- and aboveground biodiversity protection can be expected to be operational. Agroforestry systems provide sustainability and stability to agricultural production system. Now, the scientists, administrators, policy makers, and politicians are convinced that agroforestry systems not only provide livelihood sustainability but also can be used to solve the problems of modern world including mitigating climate change. Some of these ecological services are explained in brief here in this chapter.

5.3.1 Agroforestry Potentials for Rehabilitation of Degraded Lands

Indeed, no clear consensus exists as to the extent of degraded land, not only globally, but even within a particular country. Recently, Gibbs and Salmon (2015) have reviewed prominent databases and methodologies used to estimate the area of degraded lands and expressed that the global estimates of total degraded area vary from less than one billion ha to over six billion ha, with equally wide disagreement in their special distribution. The Global Assessment of Soil Degradation (GLASOD) commissioned by the United Nations Environment Program (UNEP) was the first attempt to map human-induced degradation around the world (Oldeman et al. 1990; Oldeman 1994) and is still used today (Nijsen et al. 2012). According to GACGC (1994), the main types of soil degradation are water erosion (56%), wind erosion (28%), chemical degradation (12%), and physical degradation (4%); and causes of soil degradation include overgrazing (35%), deforestation (30%), agricultural activities (27%), overexploitation of vegetation (7%), and industrial activities (1%).

It has been estimated that 580 million ha (Mha) area is degraded due to deforestation, 680 Mha due to overgrazing, 137 Mha due to fuel wood consumption, 550 Mha due to agricultural mismanagement, and 19.5 Mha due to industry and urbanization (FAO 1996). By 2008, more than 20% of all cultivated areas, 30% of natural forests, and 25% of grasslands were undergoing some degree of degradation (Bai et al. 2008). It has been estimated that up to 25% of all land is currently highly degraded, 36% is slightly or moderately degraded but in stable condition, while only 10% is improving (FAO 2011). If the current scenario of land degradation continues over the next 25 years, it may reduce global food production, from what it otherwise would be, by as much as 12% resulting in world food prices as much as 30% higher for some commodities (IFPRI 2012). This is at a time when population growth, rising incomes, and changing consumption patterns are expected to increase the demand for food, energy, and water, by at least 50%, 45%, and 30%, respectively, by 2030 (IFPRI 2012). These expected levels of global demand cannot be met sustainably unless we protect and restore the fertility of our soil and rehabilitate our degraded lands preferably following agroforestry techniques (Dagar 2012, 2015; Dagar and Gupta 2016). Agroforestry approach is viable, sustainable, and environment friendly.

5.3.1.1 Agroforestry on Eroded Lands

Soil erosion has socioeconomic, environmental, and technical dimensions. Those who suffer the most are poor farmers and landless laborers, who are least able to adopt conventional measures for its control. A more beneficial alternative in eroded ecologies both high rainfall and semiarid regions, from an ecosystem perspective, is to create a multifunctional land use system. For example, native trees can be planted together with shade-tolerant agricultural cash crops such as coffee, cocoa, cardamom, zinger or turmeric, or medicinal plants. Plantation crops like coconut are blended suitably with spices such as clove, cardamom, black pepper, and even fruits like pineapple. 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. In Sri Lanka, where 32% of the land is degraded and forest cover is declined rapidly to 21% (in 1997), the government has focused on promoting tree planting and intensification of homegardens aiming to ease pressure on forests; 13% of the country's land is devoted to homegardens. Sri Lankan homegardens are highly biodiverse, multilayered structures, with a canopy of tall trees intercepted with small trees and plantations and shrubs and planted with crops underneath. The national tree planting program "Deyata Sevana" and more recently "Divi Neguma" (livelihood development) aimed to add 1.5 million homegardens to help achieve self-sufficiency in vegetables and reduce vegetable prices; and the target later increased to 2.5 million homegardens and the program included in national climate change and mitigation and adaptation strategies, as well as in the REDD+ reforestation and land restoration program (http://www.gwp.org). Similarly, in Vietnam, farm forestry is included as ambitious reforestation policy including reforestation of five million ha (2 million ha by individual entities such as households and entrepreneurs). Millions of hectares around the world are now covered with agroforestry systems including, for example, 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). Multilayered plantation-based agroforestry systems, improved 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 found suitable for coastal and island situations, which will not only restore these ecosystems and sustain livelihood and nutrition security but also will render ecological services such as biodiversity improvement, carbon sequestration, and mitigate climate change (Dagar et al. 2014a). Sajjapongse et al. (2002) developed a sustainable alley cropping model on sloping lands in China by planting daylily (*Hemerocallis* sp.), pears (*Pyrus* spp.), and Chinese prickly ash (*Zanthoxylum* spp.) as hedgerow crops and corn, 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 arid and semiarid 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). Protection from grazing and afforestation with suitable species are found the most effective measures for checking soil erosion and consequently ravine formation.

Protection from grazing and afforestation with native tree and grass species is the most effective measure for checking soil erosion and consequently ravine formation. Woody species found growing in eroded habitats may find priority in afforestation program. For example, *Acacia nilotica*, *A. eburnea*, *A. leucophloea*, *A. catechu*, *Azadirachta indica*, *Albizia lebbeck*, *Balanites roxburghii*, *Butea monosperma*, *Dalbergia sissoo*, *Dendrocalamus strictus*, *Dichrostachys cinerea*, *Eucalyptus* spp., *Feronia limonia*, *Pongamia pinnata*, *Prosopis juliflora*, and *Ziziphus mauritiana* have been found to adapt easily in the ravines of river Yamuna at Agra and Kshipra at Ujjain. Among grasses *Dichanthium annulatum*, *Cenchrus ciliaris*, *Bothriochloa pertusa*, *Chrysopogon fulvus*, *Themeda triandra*, *Heteropogon contortus*, *Sehima nervosum*, *Tragus biflorus*, *Iseilema laxum*, *Cynodon dactylon*, and *Saccharum munja* flourish well in ravine lands. After protecting from grazing, silvopastoral system involving the above mentioned tree and grass species and introducing legumes such as *Stylosanthes*, *Alysicarpus*, etc. may be developed with great success. High-value medicinal species such as *Aloe vera*, *Ocimum americanum*, *O. sanctum*, *Withania somnifera*, *Adhatoda vasica*, *Barleria prionitis*, *Solanum xanthocarpum*, etc. and biofuels such as *Euphorbia antisyphilitica*, *Jatropha curcas*, and *Pongamia pinnata* (at the bottom of ravines) can easily be blended in these habitats.

Grass species such as Hybrid napier (*Pennisetum* × *purpureum*), *Panicum maximum*, *Chrysopogon fulvus*, *Vetiveria zizanioides*, and *Eulaliopsis binata* have been found suitable in the Shiwaliks and lower hills. Maize and wheat yield were found increased by 23–40% and 10–20%, respectively, when cultivated with grass barriers in addition to 0.6–1.7 Mg ha^{-1} yr^{-1} grass yield (Ghosh 2010). Hedgerows of trees such as *Leucaena* and *Gliricidia* are quite effective in controlling soil erosion when planted across slope. *Eucalyptus tereticornis* and Bhabar grass (*Eulaliopsis binata*) planted in Shiwaliks were found quite remunerative and effective against soil erosion (Sharda and Venkateswarlu 2007). Fruit trees such as citrus (*Citrus* spp.), mango (*Mangifera indica*), apple (*Malus pumila*), walnut (*Juglans regia*), plum (*Prunus domestica*), peach (*P. persica*), and cherry (*P. avium*) are cultivated using soil conservation practices and using mulch. Fruit trees are also grown on terrace risers in combination with vegetables. Integrated watershed management programs are being implemented in India on a massive scale since 1991, which is the most sustainable multipurpose strategy. A review of more than 300 integrated watershed management projects indicated that in majority of them total crop production increased by 50–123 percent (Joshi et al. 2005). Water harvesting technologies resulted in 50–156% increase in irrigated area under different schemes, which increased average cropping intensity by 64% (NAAS 2009). Apart from increasing agricultural productivity, these projects helped the stakeholders in generating employment, and about 47% of degraded lands have been treated for rehabilitation (Sharda et al. 2008). In remaining projects also agroforestry may be incorporated as main component particularly on highly degraded areas.

Dagar and Pathak (2005) and Pathak and Dagar (2015) while reporting the ecology and management of grazing lands in India advocated that in highly eroded habitats the first task must be protection of pasture lands from grazing followed by introduction of local trees (mainly nitrogen-fixing) and perennial grasses and legumes. Fodder banks may be established and as far as possible cut-and-carry practice must be followed or if necessary controlled grazing on regular intervals following the principle of carrying capacity should be followed. Ravenous catchments when planted with *A. nilotica* + *Dichanthium annulatum* and *D. annulatum* alone generated 5.8 and 2.6% of runoff and 1.26 and 0.62 Mg ha^{-1} of soil loss, respectively, compared to 14.7% of runoff and 3 Mg ha^{-1} of soil loss from agricultural catchments. Production of 4.5 Mg ha^{-1} air-dried grass + fire wood from such degraded lands proved the effectiveness of grasses and trees as an alternative land use for protection and productive utilization of degraded ravine lands (Sharda and Venkateswarlu 2007). Further, planting of grasses leads to improvement of soil structure and organic matter in these highly eroded habitats. Silvopastoral systems have been advocated most ideal for ravine lands and highly erodible soils (Prajapati et al. 1989; Dagar 1995, 2012, 2015; Chaturvedi et al. 2014; Dagar and Gupta 2016). Thus, suitable crop-tree-based agroforestry systems on farmers' fields and silvopastoral systems in ravine lands after protecting from grazing not only check soil erosion but also generate employment and income for different stakeholders including landless farmers residing near ravines. For details regarding ecology and rehabilitation of ravine lands, see recent publication by Dagar and Singh (2017).

5.3.1.2 Restoration of Degraded Areas Due to Shifting Cultivation

As stated earlier, shifting cultivation has become unsustainable primarily due to reduced *jhum* cycle owing to increase in population pressure resulting in serious soil erosion, depletion in soil fertility, and low productivity. As explained under improved fallows, technologies have been developed, particularly in African countries to improve the land fertility through introduction of leguminous short-duration shrubs in fallows. In Indian subcontinent, at times annual crops such as potato, rice, maize, and zinger are grown in monoculture or mixed culture along with trees like *Pinus kesiya* and *Alnus nepalensis*. Many workers (Borthakur 1992; Dhyani et al. 1996; Tripathy and Barik 2003; Tomar et al. 2012) suggested alternatives or improvements to shifting cultivation. Nair (1993) included about 44 species of perennial nitrogen-fixing woody species used in Asian farming systems which may help in improving the fallows. These include species of *Acacia*, *Albizia*, *Alnus*, *Cajanus*, *Calliandra*, *Casuarina*, *Erythrina*, *Faidherbia*, *Flemingia*, *Gliricidia*, *Leucaena*, *Parkinsonia*, *Pithecellobium*, *Pongamia*, *Prosopis*, *Robinia*, and *Sesbania*. Saha et al. (2007) reported positive effects of various multipurpose trees on physical properties of soil.

The intercropping between the fast-growing nitrogen-fixing trees during fallow phase is one of the alternative approaches to shifting cultivation. Integrated farming system approach involving fruit and forest trees, arable crops, livestock, fishery, and poultry with appropriate conservation measures for natural resources would be most effective in overall development of these areas. As the hilly region receives high rainfall, the role of trees on the terrains receives much importance and as so is the influence of agroforestry practices on soil and water resources (Singh et al. 2014). The issues which need to be settled include land tenureship, employment opportunities, skill development (e.g., basket making, cane furniture, processing of minor forest produce, honey collection, etc.), and awareness through education.

5.3.1.3 Agroforestry for Arid Ecologies

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 degradation (Dregne and Nan-Ting 1992; Oldeman 1994). Sand dunes are dominant land formation of principal hot arid zone (Africa accounts 46.1% followed by Asia 35.5%, 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 (Tewari et al. 2014). 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 brush woods 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. The vegetation for sand dune stabilization is highly drought tolerant with deep root system capable of extracting moisture from lower soil depths. Trees such as *Acacia tortilis*, *A. jacquemontii*, *A. leucophloea*, *A. senegal*, *Azadirachta indica*, *Balanites roxburghii*, *Prosopis cineraria*, *P. juliflora*, and *Holoptelea integrifolia* in combination with grasses *Cenchrus ciliaris*, *C. setigerus*, *Dichanthium annulatum*, and *Panicum antidotale* have been found most successful for sand dune stabilization. Silvopastoral system is the most viable, sustainable, and profitable system. It will also assure intangible benefits such as amelioration of soil and climate, control of soil erosion, shelter to annual crops in vicinity, and protection to wild life.

Diversified production systems appear to be very sustainable for hot arid regions. Trees like *Prosopis cineraria*, *Z. nummularia*, *Z. mauritiana*, *Tecomella undulata*, *H. binata*, *Cassia siamea*, *Acacia tortilis*, *A. nilotica*, and many others play an important role in production system. Many of these act as shelterbelt for associated crops and also improve soil health. *P. 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. Tewari et al. (2014) observed increase in available nutrients in association with trees proving that trees improve the soil health in arid ecologies.

Arable crops such as Moth (*Vigna mungo*), green gram (*V. radiata*) and cluster bean (*Cyamopsis tetragonoloba*), taramira (*Eruca sativa*), and castor (*Ricinus communis*) could successfully be cultivated when there was some rain at the time of sowing. Species suitable for shelterbelts include *Acacia tortilis*, *A. salicina*, *A. aneura*, *A. ampleceps*, *A. nilotica* ssp. *cupressiformis*, *Tamarix articulata*, *Parkinsonia aculeata*, *Prosopis juliflora*, and *Eucalyptus camaldulensis*. Following suitable techniques and protecting the area by planting close-spaced windbreaks and shelterbelts of suitable trees and using drip irrigation (even of saline water up to EC 10 dS m^{-1}), even fruit trees such as ber (*Ziziphus mauritiana*), karonda (*Carissa carandas*), pomegranate (*Punica granatum*), tamarind (*Tamarindus indica*, frost sensitive), Lasura (*Cordia rothii*, *dichotoma*), custard apple (*Annona squamosa*), and date palm (*Phoenix dactylifera*) can be raised in desert environment.

Many dry regions also have shallow soil, particularly in the eastern and south-eastern parts of Rajasthan and Kutchh area of Gujarat and also in Pakistan. 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. silicina*, *A. jacquemontii*, *P. juliflora*, *Hardwickia binata*, *Capparis decidua*, *Grewia tenax*, *Ziziphus nummularia*, *Holoptelea integrifolia*, and *Dichrostachys nutans*. Some areas in these pockets are extremely rocky and gravelly, and it was found that plantations in these areas are very difficult, and land preparation is a prerequisite. Generally, some staggered counter trenches with a cross section of 60 cm × 40 cm to minimize water erosion are constructed. Pits of 60 cm × 60 cm × 60 cm are dug out planting the seedlings. Good quality of soil from outside is filled in these pits, and seedlings of desired species are planted after adding and mixing farm yard manure (5 kg per pit) in the pits. Among successful species are *A. senegal*, *P. juliflora*, *P. chilensis*, and *Wrightia tinctoria*, while species such as *Grewia tenex*, *Z. nummularia*, and *C. decidua* may be planted with better management. Tewari and Singh (2000, 2006) and Tewari et al. (1998, 2014) have given extensive account for livelihood improvement and climate change adaptations through agroforestry in hot arid environments. Leguminous crop green gram sown under fruit tree *Ziziphus mauritiana* (cv Seb) produced 200 kg ha^{-1} grains and 800 kg ha^{-1} quality fruits (400 trees per ha) even when seasonal rainfall was 200 mm, thus rendering a drought proofing mechanism to the system. On farmers' field in Thar Desert, *Z. mauritiana-Cenchrus ciliaris* grass-based silvopastoral system proved highly remunerative, producing 2.77, 1.87 and 2.64 Mg ha^{-1} yr^{-1} fruit, leaf fodder, and fuel wood, respectively (Tewari et al. 1999, 2014).

About 11 million ha of land is desert (Thal, Thar, Choliston, and Chaki-Kharan) in Pakistan and 31.7 million ha in India, consisting of great tracts of sand dunes, which in places are interspersed with sparsely vegetated clay flats, and groundwater is highly saline EC$_{iw}$ ranging from 4 to 18 dS m^{-1}. These areas could be brought under silvopastoral system utilizing the local vegetation as well as saltbushes consisting of trees (*Prosopis cineraria*, *P. juliflora*, *Acacia nilotica*, *Tamarix articulata*, *T. indica*, *T. stricta*, *Salvadora persica*, *S. oleoides*, *Leucaena leucocephala*), and forages and grasses (*Atriplex* spp., *Maireana* spp., *Leptochloa fusca*, *Echinochloa* *crus-galli*, *Cenchrus ciliaris*, *Arthrocnemum indicum*, *Salsola drummondii*, *Bienertia cycloptera*, *Indigofera oblongifolia*, and *I. cordifolia*) using saline aquifers (Qureshi et al. 1993, Tewari et al. 2014). Further, Abdullah et al. (1993) tested 13 species of *Atriplex* and 8 of *Maireana* for their suitability in Cholistan Desert with saline irrigation (~5 dS m^{-1}) and found that species of *Atriplex* (especially *amnicola*, *bunburyana*, *halimus*, and *lentiformis*) were most promising as compared to species of *Maireana*. Al Muzaini (2003) gave environmental measures including plantation method to control sand movement in Kuwait where it has caused extensive deterioration of the desert ecosystem. Palms including date palm (*Phoenix dactylifera*) and *Eucalyptus* are found suitable for Kuwait environment. Jaradat (2003) advocated cultivation of about 200 species of halophytes (used as grains and oil seeds, fruits, forage crops, fuel, pulp and fiber, and as bioactive derivatives) for sustainable biosaline farming systems in the Middle East. In Zambia, the use of nitrogen-fixing species such as *Sesbania sesban* and *Tephrosia vogelii* could get same crop yield as fully fertilized fields and same species plus *Crotalaria grahamiana* doubled maize yields in western Kenya. Further, across Africa the use of *Faidherbia albida* in various combinations has been well proved to boost maize yields, especially in low-fertility soils (Garrity et al. 2010).

5.3.1.4 Agroforestry of 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). Aluminum (Al) in these soils is solubilized into ionic forms, especially when the soil pH falls 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 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 northeastern 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, colocacia, and taros make successful and sustainable agroforestry systems, which besides providing good economic yields also ameliorate soil by fixing nitrogen and organic matter.

In humid tropics the soils are generally acidic and low in nutrient availability. Some carry toxic levels of iron and aluminum. Yadav et al. (1983) estimated that coastal saline soils in India are spread over an area of 3.1 million ha. The low-lying coastal lands may contain acid sulfate soils derived from marine and estuarine sediments with high concentration of reduced sulfur components. Upon drainage and aeration, they undergo severe acidification bringing the pH values of the soil at times below 4 in the upper 50 cm layer. Low pH adversely affects the availability of calcium, magnesium, and other nutrients. Drainage results in more oxidation causing further soil degradation. Such lands are managed for rice cultivation and brackish water fish culture. Appropriate agroforestry systems may also prove useful in the management of acid soils as woody perennials can recycle nutrients, maintain soil organic matter, and protect the soil from erosion and runoff. The homegardens, coffee and cacao production systems, plantation-based multi-tiered dense cropping systems, and alley cropping on sloping lands represent typical agroforestry systems. Aquaculture keeping mangroves intact may be ideal, profitable, and sustainable practice in tidal zone. Dagar (1995), Kumar and Nair (2004), and Dagar et al. (2014a) have dealt with in detail some of these systems in tropical regions. On low-lying areas, rice remains important crop. Coconut, *Gliricidia*, *Ceiba pentandra*, and *Morinda citrifolia* are important boundary plantations of rice fields. Farming in forests; homegardens; plantation-based multi-tiered farming systems involving livestock, fishery, and duckry; alley cropping on sloping lands; fodder banks; and aquaculture keeping mangroves intact are some important agroforestry systems for coastal and island regions (Dagar et al. 2014a).

For the past two decades, several attempts were made to incorporate medicinal and aromatic crops in farming systems along with conventional food crops and commercial plantations. This increased land use efficiency and net return of the same piece of land (Maiti and Raju 2004). Among important medicinal and aromatic species suitable for coastal regions include *Abelmoschus moschatus*, *Acorus calamus*, *Adhatoda vasica*, *Aloe barbadensis*, *Alpinia galangal*, *Andrographis paniculata*, *Asparagus racemosus*, *Bacopa monnieri*, *Caesalpinia bonduc*, *C. crista*, *Cassia angustifolia*, *Catharanthus roseus*, *Centella asiatica*, *Clitorea ternatea*, *Coleus forskohlii*, *Curculigo orchioides*, *Curcuma longa*, *C. aromatica*, *Cynometra ramiflora*, *Cymbopogon flexuosus*, *C. martinii*, *Gloriosa superba*, *Kaempferia galangal*, *K. rotunda*, *Morinda citrifolia*, *Piper longum*, *Plumbago zeylanica*, *Pogostemon cablin*, *Solanum surattense*, *Tinospora cordifolia*, and *Zingiber officinale*.

Coastal dunes form a complex sequence of excessively drained ridges separated by poorly drained depressions. Along Orissa coast belts of cashew (*Anacardium occidentale*) plantations following the *Casuarina* line are quite common. Screw pine *Pandanus* is also quite frequent which may be explored commercially for its fruits yielding fragrant oil. *Casuarina equisetifolia* and *Eucalyptus tereticornis* are two very important trees along Andhra coast. Palmirah palm (*Borassus flabellifer*) is most frequent in agricultural fields. Mangroves form the thick belt along protected shores and creeks. These have been denuded in many areas and are in depleted condition throughout the coast. Their importance was realized during *tsunami* in December 2004 and frequent cyclones along Orissa coast. Dagar (1982, 2003, 2008) and Dagar et al. (1991, 1993) gave an illustrative account of distribution, zonation pattern, importance, and management of mangrove forests. Their role in aquaculture, shore protection, and livelihood of coastal population has been well documented. Behind mangrove belt, species such as *Pongamia pinnata*, *Terminalia catappa*, *Calophyllum inophyllum*, *Morinda citrifolia*, *Thespesia populnea*, *Cocos nucifera*, *Pandanus* spp., and *Cynometra ramiflora* can successfully be explored for their commercial importance. Mangrove Nipa palm (*Nypa fruticans*) can successfully be cultivated along creeks for alcohol production.

5.3.1.5 Agroforestry for Salt-affected and Waterlogged Lands

Salinity afflicted landscapes, which now occupy nearly a billion hectares (about 10% of land area) in the world, have their origin either by natural or man-induced causes (Szabolcs 1989), but as per FAO/UNESCO Soil Map of the World (FAO/AGL 2000), the total area of saline soils is 397 million ha (Mha) and of sodic soils 434 Mha. The salinity caused due to anthropogenic factors (secondary salinization) is related to clearing of natural deep-rooted vegetation and large-scale development of irrigated agriculture without adequate drainage. Of the current 230 Mha of irrigated land, 45 Mha is salt-affected and of almost 1500 Mha of dry land agriculture, 32 Mha are salt-affected to varying degrees by human-induced processes. Thus, globally almost 77 Mha of land is salty due to human-induced salinization (Bridges and Oldeman 1999; FAO/AGL 2000).

In alkali soils, a hard *kankar* layer of calcium carbonate is generally found at a depth of about 1.25 to 1.5 m which acts as a barrier for root penetration. The layer, therefore, has to be broken first to allow proper development of roots. However, saline soils do not require such preparation, as they do not have any such barriers. These require special techniques of afforestation so that salt contents in root zone are minimized. Pit-auger-hole technique of tree plantation has been developed and perfected (Singh et al. 1998; Dagar et al. 2001a, b; Singh and Dagar 2005) for planting trees on alkali soils. Tomar et al. (1998) conducted several long-term experiments for developing afforestation technologies on highly saline waterlogged soils. The results suggested that furrow planting improved the survival and growth of tree species as compared to ridge planting method. Besides reducing the water application costs, it improves uniformity in water application and helps in creating a favorable zone of low salinity below the sill of the furrow through downward and lateral fluxes of water making salts move away from the furrow (root zone) especially when low salinity water is used. Creation of such niches favored the establishment of young seedlings of trees. Moreover, such a system seems to be more viable from practical viewpoint of undertaking large-scale plantations of trees. Recently, Dagar (2014) and Dagar and Minhas (2016) have reviewed the agroforestry of salt-affected and waterlogged environments in detail.

On the basis of experiments conducted on highly alkali soil (pH >10), *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata*, *Eucalyptus tereticornis*, and *Parkinsonia aculeata* demonstrated a higher tolerance. Dagar et al. (2001a, b), Khan (2003), Singh et al. (2008), Dagar et al. (2013), and Dagar (2014) reported positive ameliorative effects of trees raised on highly sodic soil in terms of reduction in pH, increase in organic carbon, and available phosphorus and potassium. Earlier, Singh and Gill (1992) also reported reduction in pH from initial 10.2 to ranging from 7.9 to 8.5 in different species and increase in organic carbon from initial 0.22% to ranging from 0.62 to 0.93% and increase in available P from 28 kg ha^{-1} to 33–11 kg ha^{-1} and available K from 278 kg ha^{-1} to 359–702 kg ha^{-1} in 20-year-old plantations of *Acacia nilotica*, *Albizia lebbeck*, *Eucalyptus tereticornis*, *Prosopis juliflora*, and *Terminalia arjuna*. In that study *P. juliflora* was found most efficient in reclaiming soil in all the aspects.

In this land use system, fruit trees could be raised in wider spaces (row to row 5–6 m, at times even more, and plant to plant 4–5 m), and the arable crops were cultivated in the interspaces on high pH soils. In one trial Egyptian clover (*Trifolium alexandrinum*), wheat, rice, onion, and garlic were grown successfully for 3 years in the interspaces of fruit trees *Carissa carandas*, *Punica granatum*, *Emblica officinalis*, *Psidium guajava*, *Syzygium cumini*, and *Ziziphus mauritiana* (Tomar et al. 2004). Some of the salt-tolerant fruit trees like pomegranate (*Punica granatum*) and bael (*Aegle marmelos*) are unable to tolerate water stagnation during rainy season which should be cultivated on raised bunds (Dagar et al. 2001a). Under agroforestry systems, the bulk density of soil decreased, soil organic carbon and available nitrogen increased, and infiltration rate and water holding capacity increased considerably (Mishra et al. 2004). Medicinal liquorice (*Glycyrrhiza glabra*) has been found very interesting leguminous alkali-tolerant crop, which is not only remunerative but also ameliorates sodic as well as saline waterlogged soils (Dagar et al. 2015).

The grazing lands of salty soils are very poor in forage production under open grazing, but when brought under judicious management, these can be explored successfully for sustainable fodder production. Based on series of long-term experiments, it was found that Kallar grass (*Leptochloa fusca*) could be rated the most tolerant grass to highly sodic soil and waterlogged conditions as compared to other grasses. Among others, Rhodes grass (*Chloris gayana*), Gutton panic (*Panicum maximum*), Para grass (*Brachiaria mutica*), *Panicum antidotale*, *P. laevifolium*, *P. purpureum*, and *Setaria anceps* were successful grasses up to soil pH 9.6. These grasses can be grown successfully with most promising tree species such as *Prosopis juliflora*, *Acacia nilotica*, *Tamarix articulata*, *Casuarina equisetifolia* (susceptible for frost), *Terminalia arjuna*, and *Pongamia pinnata*. On highly sodic soil, mesquite (*Prosopis juliflora*) and Kallar grass silvopastoral practice was adjudged the most promising for fire wood and forage production and also for soil amelioration. An associative nitrogen-fixing bacterium, *Azoarcus*, occurs as an endophyte in the roots of Kallar grass (*L. fusca*) – a pioneer species of alkali soils. Symbiotic nitrogen fixation by *Rhizobium* has been extensively investigated in salt-affected soils (Rao and Ghai 1995; Rao 1998) and their survival is not a problem as they have considerable tolerance to high pH. Kaur et al. (2002) reported bio-amelioration due to silvopastoral system on highly sodic soils (pH > 10) after 7 years of plantations and concluded that grasses along with trees are more effective in bio-amelioration than sole grasses. More than 40 tree species of arid and semiarid areas were evaluated for their salinity tolerance by Tomar et al. (1998), and species like *Acacia farnesiana*, *Parkinsonia aculeata*, and *Prosopis juliflora* were rated the most tolerant to waterlogged salinity and could be grown satisfactorily on soils with salinity levels up to 50 dS m^{-1} in their root transmission zone. Tree species like *Acacia nilotica*, *A. torilis*, *Casuarina glauca*, *C. obesa*, and *C. equisetifolia* could grow on sites with ECe varying from 10 to 25 dS m^{-1}.

The saline black cotton soil zone (saline/sodic vertisols) are generally either contemporary or of secondary origin. After 14 years of plantation with several species, it was found that *P. 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*, *Vetiveria zizanioides*, and species of *Eragrostis*, *Sporobolus*, and *Panicum* were found the most successful and form suitable silvopastoral system.

Introduction of canal irrigation in arid and semiarid regions without provision of adequate drainage causes rise in groundwater table leading to waterlogging due to seepage and secondary salinization (Tewari et al. 1997). For the reclamation of waterlogged saline soils, the conventional technique is subsurface drainage which is relatively expensive and generates harmful drainage effluents and has environmental problems. A viable alternative of the above technique could be biodrainage (Jeet-Ram et al. 2011; NAAS 2015), which is "pumping of excess soil water by deep-rooted trees using bioenergy." This technique if not remediation, is at least a protective measure in potential waterlogged areas.The root systems of trees intercept saturated zone or unsaturated capillary fringe above water table to control shallow water table. These plants are known as *phreatophytes.* Fast-growing plants such as cloned *Eucalyptus* could successfully be grown on ridges particularly in areas where salinity is low. The impact of block plantations of *Eucalyptus tereticornis* on reclamation of waterlogged areas was tested and found effective at the Indira Gandhi Nahar Project (IGNP) site in Rajasthan and Dhob-Bhali research plot in Haryana (Heuperman et al. 2002; Jeet-Ram et al. 2007). On these sites it was established that the transect of trees such as species of *Eucalyptus*, *Acacia*, *Populus*, *Prosopis*, *Casuarina*, *Pongamia*, *Terminalia*, *Syzygium*, *Dalbergia*, etc. when planted along canals successfully checked seepage and helped in mitigating waterlogging. During the studies conducted in IGNP area (Heuperman et al. 2002), groundwater under the tree plantation was reported to fall by 15.7 m over a period of 6 years. At 100 m from the edge of the plantation, the level of the groundwater was about 9 m higher than at the edge, with a drawdown of 6.7 m.

Jena et al. (2011) planted *Acacia mangium* and *Casuarina equisetifolium* with intercropping of pineapple, turmeric, and arrowroot which was taken successfully in Khurda district of Orissa coast. The depth to pre-monsoon water table changed from 0.5 m to 1.67 m after 1 year of plantation and to 2.20 in next year and to 3.20 during third year due to biodrainage. Roy Chowdhury et al. (2011) also summarized the role of plantations (*Eucalyptus* and *Casuarina*) in agroforestry mode for reclamation of waterlogged situations in Deltaic Orissa. Jeet-Ram et al. (2011) observed the total drawdown of groundwater table during a period of 3 years to be 0.85 m and more than 2 m when the trees were 5 years old. The average above ground oven dry biomass was 24 Mg ha^{-1} from 240 surviving trees and the average below ground oven dry biomass of roots was 8.9 Mg ha^{-1}. The total carbon sequestration by these plantations was 15.5 Mg ha^{-1}. The wheat grains yield was 3.36 times the yield in the nearby untreated fields. Besides getting rice and wheat crops, the farmers earned additional INR 72000 ha^{-1} from *Eucalyptus* wood at a rotation of 5 years and 4 months resulting in a benefit-cost ratio of 3.5:1 at 12% discount rate of interest. Further, Dagar et al. (2016a) observed that when clonal *Eucalyptus* was planted in different spaces on bunds (adjusting 300, 200, and 100 trees per ha), timber dry wood production was 33.5 Mg ha^{-1} in spacing of 1 m × 1 m (300 trees per ha), 19.1 Mg ha^{-1} in 1 m × 2 m (200 trees per ha), and 13.5 Mg ha^{-1} in 1 m × 3 m (100 trees per ha) and sequestered 15.2, 8.9, and 6.4 Mg C ha^{-1}, respectively. Block plantations of *Eucalyptus* (4 m × 2 m spacing, 1250 trees per ha) generated 154 Mg ha^{-1} timber wood biomass and sequestered 66.5 Mg C ha^{-1}. The physicochemical properties of soil also improved to greater extent, more so in block plantations.

5.3.1.6 Agroforestry on Degraded Soil in Dry Regions Having Saline Aquifers for Irrigation

In most of the dry regions, the underground aquifers are saline. Recent research efforts have shown that these waters can successfully be explored for establishment of trees and developing suitable agroforestry systems (Dagar 2014; Dagar et al. 2014b, 2016b; Dagar and Minhas 2016; Yadav and Dagar 2016). In long-term field experiments conducted (Tomar et al. 2003b) on a highly calcareous soil (*Typic Haplustalf*) in semiarid monsoon-type climate of India, it was found that tree species such as *Tamarix articulata*, *Acacia nilotica*, *A. tortilis*, *Eucalyptus tereticornis*, *Prosopis juliflora*, and *Azadirachta indica* could successfully be established when planted and irrigated in furrows using saline water of EC 10 dS m^{-1}. Litter fall from the most of tree species resulted in an improvement in organic carbon content of the underlying soils. *Acacia nilotica*, *A. tortilis*, *Azadirachta indica*, *Eucalyptus tereticornis*, *Feronia limonia*, *Tamarix articulata*, and *Guazuma ulmifolia* species increased organic carbon content (>5 g kg^{-1}). In another long-term study, Dagar et al. (2016c) established fruit-based agroforestry systems planting karonda (*Carissa carandas*), Indian gooseberry (*Emblica officinalis*), and bael (*Aegle marmelos*) in wider spaces (4 m × 5 m) on sandy loam calcareous soil and irrigated with low (EC_{iw} ~ 4–6 dS m^{-1}, SAR 18) salinity water, alternate irrigation with water of low and high (EC_{iw} 8.5–10.0 dS m^{-1}, SAR 21) salinity, and irrigation with water of high salinity. The interspaces were cultivated with pearl millet (*Pennisetum typhoides* cv HHB 68) and cluster bean (*Cyamopsis tetragonoloba* cv HG 365) during the *kharif* (rainy) season (*Hordeum vulgare* cv BH 375) and salt-tolerant cultivar of mustard (*Brassica juncea* cv CS 54) during winter. This was most successful and remunerative system. There was nominal salinity build up when irrigated with water of high salinity, but when there was a year of normal rainfall during 3–4 years of interval, most of the salinity of root zone leached down and, thus, the system was found sustainable.

Usually salinity limit in irrigation water depends upon soil permeability and salt tolerance of cultivated trees and crops. Over irrigation with saline water at leaching fraction of about 40% results in making ECe almost equal to that of EC_{iw} at sandy strata (Ahmad and Ismail 1993a, b). This makes it possible to use water of 5–20 dS m^{-1} for raising halo-xeric forages and other crops at sandy substratum. Ahmad et al. (1987) and Ahmad and Ismail (1993a, b) 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 such as *Azadirachta indica*, *Casuarina equisetifolia*, and *Eucalyptus camaldulensis*, 25% biomass reduction started only at ECiw >15 dS m^{-1}, 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}.

Aslam et al. (1993) observed that the application of brackish water did not cause any change in soil properties. In contrast, the roots of *Kallar* grass were able to penetrate to depth creating vertical fine channels accelerating the leaching of salts down below 3 m in depth and increasing the hydraulic capacity of the soil. Thus, the cultivation of salt-tolerant plants like *Kallar* grass also initiates a soil improvement process by providing soluble Ca^{+2} to the soil through dissolution of native $CaCO_3$ which lowers the pH. Rashid et al. (1993) demonstrated in Peshawar valley that *Atriplex lentiformis* (159) was the most productive of the 20 saltbushes tested irrigating with brackish water. The other promising accessions were *A. amnicola* (971), *A. lentiformis* (178), *A. halimus*, *A. cineraria* (524), *A. undulata* (471), and *A. amnicola* (573). These saltbushes along with productive salt-tolerant grasses and forage trees may form ideal silvopastoral system on these degraded lands. Quadir et al. (1995) reported 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, 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. (2003a) found that forage grasses like *Panicum laevifolium* and *P. maximum* were most suitable species producing annually 14–17 Mg ha^{-1} dry forage showing their potential as silvopastoral grasses if grown in protected conditions.

Among nonconventional crops, castor (*Ricinus communis*), *Aloe vera*, dill (*Anethum graveolens*), and taramira (*Eruca sativa*) could be grown successfully when provided with three irrigations of saline water of EC 10 dS m^{-1} (Dagar et al. 2008). Psyllium (*Plantago ovata*) and lemongrass (*Cymbopogon flexuosus*) could also be cultivated successfully (Tomar et al. 2010; Dagar et al. 2013) with saline irrigation. Psyllium did not show any yield reduction with *Acacia* plantation even at later stages showing its suitability for partial shade tolerance. Other medicinal plants such as *Aloe barbadensis*, *Adhatoda vasica*, *Cassia angustifolia*, *Lepidium sativum*, *Withania somnifera*, *Citrullus colocynthis*, and *Catharanthus roseus* could successfully be grown with saline irrigation as intercrops or in isolation. All these high-value crops can successfully be grown as intercrops with forest or fruit trees at least during initial years of establishment (Dagar et al. 2008; Dagar and Minhas 2016). Ornamental flowers such as *Chrysanthemum*, *Calendula*, and *Matricaria* were cultivated irrigating with water of EC up to 5 dS m^{-1} yielding 13.2, 4.7, and 3.5 Mg ha^{-1}, respectively, fresh flowers in a season (Tomar and Minhas 2002). Many medicinal plants were also cultivated with saline irrigation (Tomar and Minhas 2004b). The aromatic grasses such as vetiver, lemongrass, and palmarosa, when irrigated with saline water (EC 8.5 dS m^{-1}), could produce an average 90.9, 10.4, and 24.3 Mg ha^{-1}dry biomass, respectively (Tomar and Minhas 2004a). Different cultivars of vetiver could produce 72.6 to 78.7 Mg ha^{-1}shoot biomass and 1.12 to 1.71 Mg ha^{-1} root biomass. The roots are used to extract aromatic oil. Oil (property like sperm whale) yielding *Simmondsia chinensis* and petro crop like *Euphorbia antisyphilitica* are other interesting plants having potential to be grown as commercial crops irrigating with saline water up to 8 dS m^{-1} (Dagar et al. 2012).

5.3.1.7 Rehabilitation of Mine Spoils

The mining leads to deterioration of the site to the extent that no biomass can be produced at the mined site. The process of vegetation development begins naturally through colonization by the species found in surrounding areas. Artificial seeding of quick-growing grasses may accelerate development of vegetation, improve soil fertility, moisture retaining capacity, stabilize the slopes, and encourage natural invasion of native tree and shrub saplings. Plantation of mixed tree species may be undertaken after 2–3 years of growing grasses (Singh 2004). Direct seeding of tree species for 3 years with grasses and leguminous forbs has been found to be useful (Juyal et al. 2007). Studies conducted for the limestone mine spoil revealed that 30 kg N ha^{-1} and 20 Mg ha^{-1} farm yard manure or leaf litter helped *Eulaliopsis binata* grass in establishing on such sites. In Amarkantak, 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 mines in India, while Chaturvedi et al. (2014) reported different plant species suitable for revegetation of different mine spoils which included *Eucalyptus camaldulensis*, *Grevillea pteridifolia*, *Pinus* spp., and *Shorea robusta* for bauxite mined area; *Acacia catechu*, *Agave americana*, *Arundo donax*, *Bauhinia retusa*, *Buddleja asiatica*, *Chrysopogon fulvus*, *D. sissoo*, *Erythrina suberosa*, *Eulaliopsis binata*, *Ipomea carnea*, *Leucaena leucocephala*, *Mimosa himalayana*, *Pennisetum purpureum*, *Rumex hastatus*, *Salix tetrasperma*, and *Vitex negundo* for limestone mine spoils; *Acacia auriculiformis*, *A. nilotica*, *Dalbergia sissoo*, *E. camaldulensis*, *E. hybrid*, *Pongamia pinnata*, and bamboo species for coal mines sites; *Acacia catechu*, *D. sissoo*, *L. leucocephala*, *M. himalayana*, *P. purpureum*, *R. hastatus*, *Saccharum spontaneum*, *Salix tetrasperma*, and *V. negundo* for rock phosphate mine site; *Acacia tortilis*, *A. senegal*, *Cenchrus setigerus*, *Cymbopogon* spp., *Cynodon dactylon*, *Dichanthium annulatum*, *Grewia tenax*, *P. juliflora*, *Salvadora oleoides*, *Sporobolus marginatus*, *Tamarix articulata*, *Ziziphus nummularia*, etc. for mica, copper, tungsten, marble, dolomite, limestone, etc. mine spoils; *Albizia lebbeck*, bamboos, *D. sissoo*, *Emblica officinalis*, *Eucalyptus* spp., *Leucaena leucocephala*, and local plants for iron wastes; and species of

Acacia, *Agave*, *Eucalyptus*, and *Leucaena* for lignite mines. Mine rehabilitation is a completely neglected area and needs attention in India. According to the report of the Union Ministry of Mines (Ministry of Statistics and Program Implementation), about 1135 mines covering 11,200 ha area are still under rehabilitation program. A total of 901 mines covering an area of 23,556 ha were planted with 52 million trees out of which 70% survived. This is an encouraging figure, and, hence, based on soil, ecology, and tolerance, a detailed program of rehabilitation of all mine spoils in the country must be planned.

5.3.2 Agroforestry Systems and Biodiversity

Indogenous agroforestry systems are the repositories of biodiversity in many places of the world. In most of the populated countries especially in South and Southeast Asia, tree- dominated homegardens constitute important land use, which provides them to conserve plant and other wildlife population. Tropical homegardens are the richest in biodiversity for a unit area under cultivation. According to some research findings, a total of 525 useful plant species was recorded from 163 homegardens in Tswana *tshimo* homegardens of South Africa (Molebatsi et al. 2010). Over 149 crop species were identified in homegardens of central Sulawes of Indonesia (Kehlenbeck and Maas 2004); 128 plant species from Kerala, India (Kumar 2004); 233 plant species from San Rafael Coxcatlan, Mexico (Blanckaert et al. 2004); 230 in Northeastern Thailand (Black et al. 1996); 150 in Quintan Roo, Mexico (De Clerck and Negreros 2000); 168 in Santa Rosa, Peruvian Amazon (Padoch and de Jong 1987); 250 in Catalonia, Spain (Agelet et al. 2000); 179 in West Java, Indonesia (Soemarwoto 1987); 272 plant species in a hamlet of 41 households (Soemarwoto and Conway 1992; 76 plant species in the homegarden of the offshore island of Bangladesh (Alam and Masum 2005); 84 plant species in the homegardens of Tigray, Ethiopia (Hintsa 2012); and 66 useful species are cultivated in Andaman-Nicobar Islands (Dagar 1995), but relatively small amount of plant species recorded in El Obeid, Central Sudan; 32 different plant species in 81 homegardens (Gebauer 2005). In Bangladesh, more than 20 million households have homegardens covering sabout 12% of the total land area of the country. A survey in more than 400 homegardens revealed 419 plant species found in these gardens, which included six on the IUCN Red List for Bangladesh (Webb and Kabir 2009). Because of their richness in plant species, homegardens are regarded as an ideal production system for in situ conservation of plant species. The greater the diversity means, the greater the chance for adaptation by the local people. However, Abebe et al. (2010) studies illustrate that the species diversity is often not static, but changes in response to socioeconomic dynamics. Consequently, homegardens should not be interpreted as a generic agroforestry system with uniform diversity characteristics, but rather as involving different types with specific features in respect to species diversity.

Different literatures showed that dryland homegarden agroforestry play a major role in the conservation of plant species (Wezel and Bender 2003; Gebauer 2005; Hintsa 2012; Hintsa and Emiru 2016). Moreover, the presence of woody species in homegarden agroforestry may favor the survival of other living organisms and hence contribute to a wider conservation of biological diversity. Homegarden agroforestry is the alternative for biodiversity conservation in environmental limited areas like dry land areas. The variation in species richness in different dryland homegarden agroforestry is related to ecological, cultural, and socioeconomic conditions. For instance, homegardens in the highland humid tropics are expected to be rich in species as compared to the highland semiarid tropics because of rainfall and temperature is very suitable.

Another one of the richest ecosystems in biodiversity are mangrove stands. Besides being rich in floral diversity, these also give shelter to variety of wildlife. Most of the coastal aquatic animals including fish utilize the mangrove water as nursery and breeding grounds. A variety of animals (including benthic organisms) associates with mangroves and make complex but interesting food web. Mangroves not only protect coast but also contribute substantially the nutrients to fishery in the adjacent waters. There are many forms of aquaculture, such as oyster, crab, fish, and shrimp culture enclosed either in pans or cages, which may be undertaken without distruction of mangroves. In many areas shrimp culture is followed behind mangroves in constructed ponds. Species of *Avicennia*, *Ceriops*, *Rhizophora*, *Sonneratia*, *Bruguera*, and *Cynometra* and many associate species are good fodders and may be grown in paired rows in mangrove swamps. In many reclaimed areas, coconut and *Morinda citrifolia* are grown on bunds, and fish is cultivated in channels. Integrated farming system involving aquaculture, poultry, animals, plantation crops, fruit trees, tree spices, black pepper, etc. on uplands and rice-cum-fish on lowlands in most of the coastal areas, which in turn also is rich in biodiversity and highly remunerative (for more details, see Dagar et al. 2014a).

5.3.3 Agroforestry for Carbon Sequestration and Mitigation of Climate Change

The agricultural systems are already affected by unsustainable management and land and resource degradation and further are the most vulnerable to climate change. Managed agroforestry has an important role to play not only in climate change mitigation (following smart agriculture practices) but also in reducing vulnerability to climate-related risks because of a variety of components. Based on the papers presented during Second World Congress of Agroforestry held in Kenya in 2009, Nair and Garrity (2012a) compiled the comprehensive account of agroforestry research and advancement including the role of agroforestry to be played to mitigate climate change. The chapters written by Leakey (2012), Swaminathan (2012), Nair (2012), Minang et al. (2012), Mosquera-Losada et al. (2012), and Nair and Garrity (2012b) are of great significance in this direction. Citing the recognition of the fact by IPCC (Intergovernmental Panel on Climate Change), Swaminathan (2012) and Dagar et al. (2016b) mentioned that agroforestry systems have the highest carbon sequestration potential among managed land use systems, followed by grazing management, forest management, and crop plant management in that order. He further mentioned the agroforestry opportunities in mangrove areas, which have tremendous potential for carbon sequestration, biodiversity conservation, and enhancing aquatic productivity. This ecosystem is attaining attention only now because of the alarm about the rise of sea levels. Mangroves along with other halophytes such as species of *Salicornia*, *Salvadora*, *Suaeda*, *Atriplex*, and *Arthrocnemum* have a great deal of value as repository genes for salinity tolerance. Further, roots and leaf exudates of the mangroves those are rich in nutrients support shrimp and fish production. As mentioned earlier "agro-aqua" farm cultivation with halophytes can be a good strategy for mangrove protection and sequestering huge amount of carbon. These have reputation of increased protection of coastal areas to erosion and storm surges. There is evidence that many types of coastal forests can help dissipate wave energy and force, reducing flooding, and also help to capture debris that would otherwise do more damage, Further, the recommended greenbelt width for protective mangroves varies from 100 m for *tsunami* protection in the Asia South Pacific to 200 m for protection of agricultural lands (Pro Act 2008), suggesting that carbon sequestration potential may be significant.

Agroforestry system has attracted special attention in climate change mitigation and adaptations. However, the site-specific nature of these systems and lack of uniformity in C sequestration estimation methods make it difficult to compare the reported results. Nair (2012) 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 as 700, 100, 300, 450, and 50 million ha, respectively. Glenn et al. (1992) estimated that 0.6–1.2 gigatonnes (Gt) of C per year could be assimilated annually by halophytes on saline soils; evidence from decomposition experiments suggested that 30–50% of this carbon might enter long-term storage in soil. Thus, halophytes adapted to saline soils could play an important role in soil carbon sequestration. Bhojvaid and Timmer (1998) showed the annual rate of increase of 1.4 Mg C ha^{-1} yr^{-1} over a 30 years' period of plantation of *Prosopis juliflora* on highly sodic soil. In silvopastoral agroforestry systems on sodic soils in northwest India, the total carbon storage was 1.18–18.55 Mg C ha^{-1}, and carbon input in net primary production varied between 0.98 and 6.50 Mg C ha^{-1} year^{-1} (Kaur et al. 2002). The aboveground woody biomass carbon in *Prosopis juliflora* + *Desmostachya bipinnata* silvopastral systems, bole, and branches comprised 82% of the total biomass carbon in 6-year-old systems (Kaur et al. 2002). Total carbon storage was 18.54 to 12.17 Mg C ha^{-1}, and carbon input in net primary production varied between 6.50 and 3.24 Mg C ha^{-1} year^{-1}. In southwestern Australia, the rates of C sequestration in biomass of *Eucalyptus globulus* over a 10-year period ranged from 3.3 to 11.5 Mg C ha^{-1} year^{-1} on a large-scale watershed, the rates of C sequestration being high (Harper et al. 2005, 2007).

Carbon sequestration was estimated both in plant biomass and soil in two pasture systems (*Cenchrus ciliaris* and *Cenchrus setigerus*), two tree systems (*Acacia tortilis* and *Azadirachta indica*), and four silvopastoral systems (combination of one tree and on grass) on moderately alkaline soils (pH 8.36 to 8.41) in Kachchh, Gujarat, northwestern India (Mangalassery et al. 2014). This study showed that maximum carbon was sequestered by silvipastoral system of *Acacia* + *C. ciliaris* (6.82 Mg C ha^{-1}) followed by A*cacia* + *C. setigerus* (6.15 Mg C ha^{-1}) compared to 6.02 Mg C ha^{-1} sequestered by sole plantation of *Acacia tortilis*. The silvipastoral system of *Azadirachta indica* + *C. ciliaris* and *A. indica* + *C. setigerus* registered a total carbon stock of 4.91 and 4.87 Mg C ha^{-1}, respectively, against sole plantation of *A. indica* (3.64 Mg C ha^{-1}). The silvopastoral system sequestered 36.3%–60.0% more total soil organic carbon stock compared to the tree system and 27.1–70.8% more in comparison to the grass alone. Thus, silvopastoral system sequestered more carbon (Mangalassery et al. 2014).

Neumann et al. (2011) have provided estimates of carbon sequestration and biomass production rates from agroforestry in lower rainfall zones (300–650 mm) of Southern Murray-Darling Basin Region on the basis of data of agroforestry on 121 sites (32 species); the average age of the plantings in this study was 16.5 years, with plantation ages ranging from 5.7 to 99 years since establishment. Potential productivity was found to be highly variable and influenced by species choices, planting designs, land management practices, and climatic conditions. Preliminary assessments suggested that the average aboveground carbon sequestration rates across the region were 9.5 Mg of carbon dioxide equivalents ha^{-1} yr^{-1} (CO_2-e Mg ha^{-1} yr^{-1}) for all measured plantations (Neumann et al. 2011). For tree-form eucalyptus, the rate was similar, i.e., 10.6 CO_2-e Mg ha^{-1} yr^{-1}, while formallee-form eucalyptus, it was 6.3 CO_2-e M ha^{-1} yr^{-1} and for non-eucalyptus trees it was 6.9 CO_2-e M ha^{-1} yr^{-1}. In these lower rainfall areas, growth and sequestration rates are naturally slower and mallees could be the best option (Neumann et al. 2011).

Nair (2012) stated that 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. Based on SWOT analysis, he 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.

5.3.4 Sociocultural and Recreational Value

The indigenous and traditional systems have been appreciated for ecological principles and sustainability; but very little attention has been paid toward the recreational and cultural values of the systems. Wherever these systems are practiced, these are an important component of local cultural heritage. The indigenous bamboo + pine system and the rice + fish culture of the Apatani tribe of Arunachal Pradesh in India have earned the rare distinction as a UNESCO World Heritage Site for its extremely high productivity and the unique way of preserving the ecology (Tangjang and Nair 2016). The Saharia tribes from central India traditionally collect leaves of *Butea monosperma* for making platter cups (dona patta) and collect gum of commerce from the same tree without damaging the ecology. This is cultural tradition of earning livelihood from the natural stands of these trees. Similarly, broom making from wild palm (*Phoenix sylvestris*) is commonly prevalent in Bargundas belonging to Khajuravanshi community from Khandwa region of Madhya Pradesh in India (Ram-Newaj et al. 2016). They also use fruits as edible and ooze a fluid used as Toddy or Neera, jiggery from fruit juice leaves for making brooms, baskets, fans, floor mats, etc. Thus, there are many unrecorded cultural tales associated with traditional agroforestry systems which need documentation.

5.4 Alley Cropping

Alley cropping though is considered a modern system but it is not new concept. During 1930s the Dutch system 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 colonized widely due to lack of management. However, during the 1970s through the combined efforts of the local extension service, the Leucaena contour terracing system together with management was successfully introduced in the island of Flores in Indonesia (Parera 1989; Kang et al. 1990). The system, locally known as *Lamtoronisasi*, was adopted widely. A similar system known as sloping agricultural land technology (SALT) is also used in the Philippines (Laquihon and Watson 1986). Further, during 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 development of and research on the alley cropping system (Kang et al. 1981, 1990).

In recent times, substantial research has been put into alley cropping (hedgerow intercropping) system in which usually arable crops are grown in alleys formed by hedgerows of trees or shrubs. The system is more effective and useful for sloping lands in high rainfall areas where problem of soil erosion is acute. The hedgerows are cut back at crop planting time and kept pruned during the cropping season to prevent shading and to reduce competition with food crops. The hedgerows are allowed to grow when there are no crops and normally pruned during the season, and the pruned material is either used as mulch or as source of green manuring or sometimes also as fodder. Tree species such as *Leucaena leucocephala*, *Gliricidia sepium*, *Cassia seamea*, and *Sesbania sesban* have already been tested for their efficiency. Short duration rainy crops such as pearl millet and sorghum were found to be compatible with *Leucaena* and *Gliricidia*. In high rainfall areas, *Gliricidia* has been found very successful on sloping lands, and forage grasses such as *Pennisetum purpureum*, *P. polystachion*, *Seteria anceps*, and legume *Stylosanthes guianensis* grown as fodder crops found effective which in turn also helped in checking soil erosion. Other crops such as turmeric, ginger, colocasia, yams, etc. were also grown as cover crops. Hedgerows are generally used for production of fodder, fuel wood, mulch production, nutrient yield (nitrogen fixation), weed control, and protection of soil from erosion. Since the pioneer studies by Kang et al. (1990) for mostly African countries, the system has been worked out globaly for standardization of space, nutrient interaction, and tree-crop interactions. Rao et al. (1991), Korwar (1992, 1999), and Osman et al. (1998) have reported interesting results from India.

5.5 Parklands Agroforestry Systems

Parklands constitute the predominant agroforestry systems in semiarid West Africa. In the Sahelian zone, crops grown under discontinued cover of scattered trees are dominant in many landscapes and constitute so-called parklands. These are playing an important role through trees and shrubs in providing soil cover that reduces erosion and buffers the impacts of climate change. They provide green fodder for livestock feeds, and fruits and leaves for human consumption and income generation. Some parklands are mono-specific (e.g., *Fadherbia albida* and *Borassus aethiopum* based), but others have dominant tree species mixed with a range of tree and shrub species (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. 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 in these countries and combine with 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 et al. 2012). The sale of these products contributes 25–75% of annual household revenue in Mali (Faye et al. 2010), with some having international market.

5.6 Domestication of Wild Fruit Trees

Selecting superior trees from the wild; improving their desirable characteristics such as early bearing, taste, quality, and nutrition value; and popularizing them among farmers have to go a long way in ensuring food and nutritional security of the local people. Some small-scale farmers in Western and Southern Africa are diversifying high-value enterprises that involve production, processing, and commercialization of fruits from indigenous fruit trees and their products (Maathai 2012). The Miombo woodlands are rich in edible indigenous fruit trees and species such as *Sclerocarya birrea*, *Strychnos cocculoides*, *Uapaca kirkiana*, *Vangueria infausta*, *Parinari curatellifolia*, *Ziziphus mauritiana*, and *Adansonia digitata*, many of which are traded in the region. Farmers have indigenous knowledge about the importance of many of these trees and, hence, their participation is valuable for any domestication program. Farmers have been trained in techniques of germplasm collection based on wanted traits, nursery management, propagation, tree cultivation, and postharvest processing. As seeds of most of the species have short viability, their collection and germination have to be rapid.

Market research has indicated that traders want a consistent and regular supply of uniform fruits of good quality, which cannot be accomplished from wild collection and, therefore, domestication is the best way to achieve uniformity and superior quality and regular supply. As a part of a participatory tree domestication program, rural communities in many Western and Southern African countries, particularly women farmer are establishing provenance/progeny tests of several fruit tree species in their parklands. They have also been trained in postharvest handling and value addition such as preparing juice, jelly, and other products from fruits.

5.7 Commercial Agroforestry Plantations

Most of the commercial tree plantations are monocultures, e.g., oil palm and rubber plantations. But many commercial commodities are obtained with support of tree-crop intercropping. For example, tea and coffee are cultivated under partial shade and so is true for tropical spices (black pepper, clove, cardamom, cinnamon) which are cultivated in multi-tiered cropping systems. In Indo-Gangetic plains, trees like poplar *(Populus deltoides*) and *Eucalyptus* are grown on farmers' fields on bunds or as part of farming system in wider spaces, and crops are cultivated in the interspaces. Now, many improved clones have been developed in some fast-growing trees such as *Casuarina*, *Populus*, *Eucalyptus*, *Dalbergia*, *Melia*, etc. for uniform and faster growth. Parthiban (2016) and Singh (2016) have found industrial agroforestry as a successful value chain model, which has been implemented in southern states of India, though it has production and processing constraints, but with more technological and policy interventions, it may lead to advantage to the farming community in times to come.

5.8 Urban and Peri-Urban Plantations/Agroforestry

These days the contributions of urban and peri-urban agroforestry, particularly ornamental trees and palms, ornamental hedges, and flower-yielding plants are immense to the quality of urban life and general environment. Most of the public parks and landscapes are developed having lush green grasses, flowers, and trees. Many people also cultivate cut flowers and vegetables along with a few fruit trees in their courtyards. Urban agroforestry is a quite old system and developed along with the development of cities; but in recent times through new approaches, urban forestry and urban agriculture join forces in supporting livelihoods. A review of the current status of urban forestry research and development, policy-making, implementation, and education across the globe shows that advances have indeed been made (van Veenhuizen 2006). Urban forestry has been developed in response to the call for innovative, comprehensive concepts that promote the multiple benefits of urban greenspace. Trees can help improve livelihoods, temper harsh urban climates, conserve biodiversity, and contribute to better human health by reducing air pollution. During recent years, integrative and strategic concepts and fields of activity have been developed and implemented across the globe to promote and develop tree-based resources catering to multiple urban demands. In the industrialized countries, cities have often turned to green areas for providing attractive environments for businesses to settle in and people to live in (Konijnendijk 2003). The generally positive impact of nearby well-managed forests, green areas, and trees on real estate prices and business development has been documented during recent years, for instance, through hedonic pricing studies (Wolf 2004; Tyrväinen et al. 2005).

Many of the world's largest cities rely on fully or partially protected forests in nearby or more remote catchment areas for much of their drinking water. Additional protective measures are often needed to ensure high-quality drinking water from these watersheds (Dudley and Stolton 2003). Trees also act as shelterbelts in cold as well as arid regions to stop the sand movements; and also intercept particles and gaseous pollutants and thus help reduce air pollution. Establishing woodlots in villages close to the urban centers relieves the pressure on natural forests for fuel wood, poles, and fodder as in many developing countries population in cities still depends on fuel wood. Urban and peri-urban forests can enhance urban agricultural production, primarily in agroforestry systems (FAO 2003; Akinbamijo 2004; Yadav and Dagar 2016; Yadav et al. 2016).

In many developing countries, disposal of sewage water is a problem. Out of estimated 356 km^3 per year of total wastewater generated across all the continents (Sato et al. 2013), only 50% is treated to primary level. In developing countries of the Middle East and North Africa, Latin America, and Asia, only 8%, 18%, and 32%, respectively, of total wastewater generated is treated. Overall, about 20 million ha of agricultural land is irrigated with treated and untreated wastewater throughout the world. Such practice has resulted in the potential health risks due to pathogens, salts, nutrients, and toxic elements in food chain. Many studies have been conducted and reported in Egypt (Braatz and Kandiah 1998; Omran et al. 1998), Australia (CSIRO 1995; Duncan et al. 1998; Lone et al. 2008), India (Das and Kaul 1992; Minhas et al. 2015; Yadav and Dagar 2016; Yadav et al. 2016), and many other countries on utilization of sewage water for raising trees, which comparative to food crops absorb and lock up more amount of the toxic elements in wood. Trees like *Acacia nilotica*, *A. salicina*, *Casuarina glauca*, *C. equisetifolia*, *Eucalyptus camaldulensis*, *E. globulus*, *E. grandis*, *E. tereticornis*, *Pinus eldarica*, *P. resinosa*, and many other species grow faster with sewage water irrigation comparative to normal water because of availability of more nutrients in sewage water. Many of these such as *Eucalyptus* evaporate huge amount of water reducing the problem of disposal. The use of tree plantations continues to be investigated globally for sustainable disposal or reuse of wastewater, improving livelihood security of million of smallholders in peri-urban areas (Quadir et al. 2010), impact on soil fertility (Yadav et al. 2003; Kumar and Reddy 2010; Tabari et al. 2011), phytoremediation (Tangahu et al. 2011; Lal et al. 2016), soil reclamation (Lone et al. 2008), creation of wetlands for improving biodiversity (Quadir et al. 2010), environmental services (Dagar 2014; Gupta and Dagar 2016a,b), and potential as carbon sequestration and climate change adaptation measures (Minhas et al. 2015; Yadav and Dagar 2016). It has been advocated that the sewage water can successfully be utilized for sustainable and high economic gains in agroforestry mode if we grow high-value crops such as cut flowers like marigold (*Tagetes erecta*), *Chrysanthemum indicum*, and *Gladiolus grandiflorus* and aromatic oil-yielding crops such as lemongrass (*Cymbopogon flexuosus*), palmarosa (*C. martinii*), German chamomile (*Matricaria chamomilla*), vetiver (*Vetiveria zizanioides*), etc. whose products in use (aromatic oil) do not come in food chain, along with trees like *Eucalyptus tereticornis* and *Populus deltoides*. Many trees and crops absorb heavy metals and act as phytoremediation agents (Ebbs et al. 1997; Tangahu et al. 2011; Lal et al. 2013).

Due to lack of awareness about the concept, lack of information exchange, and lack of strategic and coordinated action for implementation of afforestation programs and policies, the full potential of the urban agroforestry concept remains to be realized. FAO has been among the first organizations taking up the challenge of promoting the concept – under the name urban and peri-urban forestry – as a framework for action, with emphasis on the developing countries and countries with economies in transition and urban forestry's contributions to food security and poverty alleviation. The Forestry Outlook Study for West and Central Asia (FOWECA) is one among a series of regional forestry sector outlook studies initiated by FAO in collaboration with member countries to examine the trends in the development of forests and forestry (FAO 2004).

The primary objective of FOWECA is toprovide a long-term perspective of the development of the forestry sector in the West and Central Asia region in the context of economic, social, institutional, and technological changes. Using 2020 as a reference year, FOWECA aims at analyzing the trends and driving forces that will shape the sector during the next two decades and at identifying policies, programs, and investment options that can enhance the sector's contribution to sustainable development. More research inputs are required in this field, particularly about developing green belts, shelterbelts, landscapes, in-house greenry, roadside plantations, and woodlots particularly utilizing sewage water. Attention may also be paid in roof cultivation and water harvesting technologies and commercial and integrated agroforestry in peri-urban areas.

6 The Way Forward

As of today, agroforestry is considered as a problem-solving science, which is based upon solid ecological principles, and in addition to that it has inbuilt social and economical linkages. While sustainability, multifunctionality, and high sociocultural values are common strength, in general, low levels of production, lack of advance research, and technological inputs to improve the systems are the major weaknesses. There are emmense opportunities to take this science forward provided government policies are favorable. With global awareness about the role of agroforestry in mitigating climate change, the future of global agriculture lies with agroforestry.

The forest cover across the world is dwindling; it will be the trees outside forest, which will enhance tree cover more so as farm forestry. In a way forward toward climate justice, agroforestry becomes a potent instrument of resilience building for vulnerable, resource-poor communities; its potential for adaptation to climate change needs to be mainstreamed and highlighted in all measures related to farmers' welfare. All kinds of degraded lands (including those are suffering from secondary salinization) are to be brought under agroforestry systems in a mission mode. Farmers, particularly, those who are resource poor would have to be facilitated and given inter alia incentives for practicing agroforestry in the context of environmental services through proper pricing, credit, insurance, marketing, etc.

The tree species already identified for promoting agroforestry need to be denotified immediately as per their agroecological zone suitability. Special efforts are needed now to produce high-quality planting material of elite varieties so identified by the research institutions, associated with much needed certification and accreditation systems. National sustainable development strategies should integrate agroforestry more fully into key areas such as poverty elevation, rural livelihood security, skill development, natural resources management, agricultural productivity enhancement, and restoration of degraded landscapes, so as to contribute more effectively toward India's intended nationally determined contribution to the UNFCCC. Public and private sector investments in agroforestry projects and programs related to research, extension, enterprise, and education be encouraged and incentivized; and innovative financial mechanisms, including climate finance for agroforestry be developed.

In regional context, agroforestry needs to be recognized as a distinct subsector under agriculture. The nodal ministry and/or agency for dealing matters relating to agroforestry needs to be clearly demarcated/nominated at the national and subnational (local) levels. Development of country-specific national policies on agroforestry and enabling mechanisms for their implementations need to be given high priority. Indian experience, ICRAF's experience, APAARI's facilitating role, and assistance from international agencies could be useful to further this initiative. A regional/international consortium-cum-network on agroforestry with a facilitation role of ICRAF, in partnership with APAARI, needs to be initiated quickly to ensure policy advocacy, public awareness, knowledge and research germplasm sharing, and capacity development and to accelerate much needed collective regional actions. The development of sound regional database, information system, and eco-region-based decision support system should receive high priority for the proposed network. Sharing of success stories of countries in the region also needs to be encouraged through open access to relevant information. An independent scientific study be undertaken to identify and assess the determinants for the scaling up of agroforestry products including market mechanism, import and export policies, and support prices, etc. Efficacy of communication and mass awareness strategies may be considered to promote agroforestry among all stakeholders. Investments, being critical for agroforestry research, teaching, training, and extension, should be at least doubled to promote agroforestry in the national and regional interests.

Medium to long-term collaborator studies to quantify contribution of agroforestry to ecosystem services, carbon sequestration, and climate change mitigation and adaptation need to be institutionalized by IARCs and the regional institutions. Awareness for public-private partnership through creation of enabling environment such as process patenting, branding, and incentives to both producers and industry needs to be created to promote further agroforestry in the region. Development of agroforestry value chains would be critical for scaling up promising innovations and to create win-win situations in the agroforestry subsector. Business planning and development involving all stakeholders in the value chain (farmer to consumer) needs to be institutionalized in a mission mode approach. Development of elite multiple-stress-tolerant germplasm and making it available for stakeholders on affordable price, establishment of acredated nurseries in large number, value addition to agroforestry products, domestication of high-value agroforestry crops, and evolving stable and sustainable marketing mechanism need attention as policy initiatives.

7 Conclusions

Agroforestry research now has provided powerful technological and policy innovations that are rapidly spreading in Africa, Asia, Latin America, and more recently in several developed countries. Now, agroforestry systems are not only for sustainable production but are also problem-solving mechanism. For example, for rehabilitation of degraded lands, mitigating climate change through carbon sequestration, employment generation, and food and nutrient security agroforestry systems are playing a vital role. Agroforestry plays important role in rehabilitation and biological reclamation of problem soils such as degraded dry lands prone to water and wind erosion including sand dunes; acid sulphate soils of humid regions characterized by low pH, toxicity of aluminum, and iron and deficiency of nutrients; salt-affected sodic and saline soils; and waterlogged saline soils. Profitable agriculture is possible if appropriate agroforestry technologies and know how are used judiciously. For checking wind erosion, windbreaks and shelterbelts involving appropriate species which require less water, possess deep root system, can be established easily with less water, and grow fast will be useful tools. The trees and shrubs will play major role in improving efficiency of nutrient cycling in the system.

Biological barriers such as alley cropping and plugging in ravines, involving appropriate species play important role in checking water erosion in sloping and ravine lands. The highly alkali soils (pH > 10) may be rehabilitated with identified tree. The saline soils may be successfully brought under vegetation cover following suitable planting techniques. For arid soils, proper agroforestry systems may be established successfully using saline water for irrigation. The tree species not only produced economic yields in terms of wood biomass but also improved soil conditions, i.e., in terms of organic matter and physical properties. Fruit-based agroforestry system involving trees and low water requiring crops such as cluster bean, pearl millet, mustard, and barley as intercrops is most suitable for calcareous soils irrigating with saline water. Nonconventional crops such as castor, *Aloe vera*, dill, taramira (*Eruca sativa*), Isabgol, senna, and lemongrass could be cultivated successfully. Biodrainage involving fast-growing trees like *Eucalyptus* and *Populus* is an eco-friendly agroforestry technique to combat waterlogging, increase farmers' income, and sequester carbon. Agroforestry helps in improving both below and aboveground biodiversity and provides opportunities to meet the livelihood security of poor and landless masses and mitigate climate change and several other ecological services. For a successful action plan, we need agroforestry and farmer friendly policies both at national and regional level. If implemented seriously, there is no reason that the problem of poverty and malnutrition is not solved at global level along with mitigating climate change and having environmental benefits.

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Chapter 3
Traditional Agroforestry Systems

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Abstract Traditional agroforestry systems (TAFS) 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 practiced across the world with varying structure, function, socio-economic attributes and ecological services. TAFS are distributed worldwide though predominantly in the tropics across Asia, Africa, South America and Pacific islands. They have been reported in temperate regions across Europe and North America too in a much more contrasting spatial and temporal pattern as compared to tropics. Among TAFS, homegardens and variants of multi-storeyed cropping systems seem to dominate in the Asian, African and Latin America. There are plenty of similarities in phytosociology, structure and diversity of homegardens whether it is in Kerala, Sri Lanka, the Philippines, Indonesia, Tanzania, Amazonian belt in Peru and Brazil, Honduras or in Pacific islands. In the Indian context, scattered trees on croplands like silvopasture system focusing on some particular species like *Acacia leucophloea*, *Acacia nilotica*, *Prosopis cineraria* and *Ficus* spp. appear to have been reported prominently and characterized by its specificity. Indeed, stark similarities in structure and function with the parkland systems of West African region dominated by *Faidherbia (Acacia) albida* and with the *Quercus suber*-dominated Dehesa system of Mediterranean Europe and the fruit tree-dominated landscapes in other parts of Europe like England, France and Germany are noticeable. Invariably in almost all TAFS, native trees appear to predominate and have a major structural, functional and service role to play whether it is in the tropics, subtopics or temperate regions across the globe. Some of the prominent traditional agroforestry systems and practices reported in scientific literature are compiled in this chapter.

Keywords Agroforestry · Multifunctionality · Multipurpose trees · Traditional knowledge · Sustainability

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1 Introduction

'Agroforestry' in very simple terms may be referred to as the deliberate growing of woody perennials on the same area and at the same time as agricultural crops and/or fodder plants in the form of a spatial mixture and/or a temporal sequence. However, there is a subtle difference in traditional agroforestry systems (TAFS) as compared to the classical understanding of agroforestry, and that difference is notable in longevity and degree of intensification. 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 practiced across the world with varying structure, function, socio-economic attributes and ecological services. They are found across the globe mainly in the tropics, subtropics and even temperate regions across Asia, Africa, Europe, North America, South America and Pacific islands, though less studied scientifically. This chapter has attempted to document and describe some of the prominent traditional agroforestry systems and practices across various continents which have been cited in literature in some form or other.

2 Traditional Agroforestry Systems in Asia

In this section various traditional agroforestry systems of India, Sri Lanka, Indonesia, the Philippines and Japan have been described.

2.1 Traditional Agroforestry Systems in India

2.1.1 Scattered Trees on Crop Field

Agroforestry in some form or other is practiced in almost all ecological and geographical regions of India. However, the systems vary enormously in their structural complexity, species diversity, productive and protective attributes and in socio-economic dimensions. It may range from apparently simple forms of shifting cultivation to complex homegardens, from systems involving sparse stands of trees on farmlands (e.g. *Prosopis cineraria* (Khejri)) tree in arid regions of Western India to high-density complex multi-storeyed homesteads of humid lowlands and from systems in which trees play predominantly 'service role' (e.g. shelter belts) to those in which they provide main saleable products (e.g. intercropping with plantation crops).

2.1.1.1 The *Acacia nilotica* System of Chhattisgarh (Central India)

This is a system practiced mainly by smallholder farmers in Madhya Pradesh in which *Acacia nilotica*, locally known as *babul*, is grown in rice fields. Farm animals have a role in the natural regeneration of babul trees in crop fields. Even though there is profuse regeneration, thinning is practiced, and an optimum spacing of around 10 m is maintained by the end of fifth year. Pruning commences in the third year of establishment of the tree and is a regular feature every summer until the final tree harvest. The trees are pruned initially in such a way to promote the formation of a clean straight bole that can fetch premium price in the market. The crown is maintained high and light by pruning off the lower branches so that the shade cast on the understorey crops is minimized (Viswanath et al. 2000).

A separate calendar of farm activities is practiced in this agroforestry system for both agriculture and forest species. Agricultural activities include land levelling, bund repair and strengthening, collection and burning of stubbles, summer ploughing, application of manure, ploughing and broadcast of rice, planting of crops on bunds, weeding, fertilizer application and plant protection, sowing of relay crop, rice harvest and bundling, threshing, winnowing and bagging. This is also followed by harvest of crop on bunds, its threshing and winnowing, followed by harvest of relay crop and its postharvest operations. Major events in *Acacia nilotica* management timeline include seed germination, initial seedling establishment, canopy management and pruning, fuel wood collection and stocking, bio-fencing, pruning of roots and branches, seed and gum collection, thinning, harvest and extraction. By practicing this agroforestry (rice + babul) system, farmers get higher cash returns on a short-term (10-year) harvest cycle of trees, and the labour input (both family and hired) on farms was distributed more uniformly throughout the year than in rice monoculture (Viswanath et al. 2000) (Fig. 3.1).

2.1.1.2 The *Prosopis cineraria* 'Khejri' System of Rajasthan, (Western India)

Prosopis cineraria in Rajasthan and *Faidherbia albida* (syn. *Acacia albida*) in Sahelian Africa are the lynchpins of traditional agroforestry system located at the interface of rain-fed agriculture and silvopastoralism. The species in Rajasthan, Western India, known as 'Khejri', is a versatile multipurpose tree which provides fodder (leaves and pods of high digestibility and nutritive value), fuel wood (high calorific value), thorny twigs as fencing materials, medicinal products from its bark and various other specific secondary products (food, crafts, etc.). The tree, which is drought resistant, mainly due to its long extensive tap root system, can draw water from the deepest layers of the soil and is also well known for its ability to maintain soil fertility. It is an appropriate, less competitive species in a subsistence system, evolved over the ages in areas where rainfall ranges from 100 to 350 mm per year (arid climates). In Rajasthan, 'Khejri' trees are maintained in croplands in a scattered way (sometimes on boundaries) in association with cereals and pulses at a density of 5–80 trees per hectare. Khejri is a slow-growing species in its early stage,

Fig. 3.1 *Acacia nilotica* trees in rice fields with sesame (*Sesamum indicum*) in risers in Chattisgarh, Central India (Photo credit: PKR Nair)

with low fodder production and limited soil beneficial effects in the initial years. Farmers continue to maintain it in their fields to sustain crop production and feed their livestock, while the droppings contribute to the much needed maintenance of soil fertility of the desert landscape (Depommier 2003).

Thus, maintenance of favourable soil moisture and improvement in the soil physical and fertility conditions by *P. cineraria* make this tree suitable for agrisilvicultural and silvopastoral systems. Lopping of tree just before the cropping season eliminates the adverse effects of shading on the understorey crop (Shankarnarayan et al. 1987) (Fig. 3.2).

2.1.1.3 Ficus-Based System of Mandya, Karnataka (South India)

In Mandya district of southern dry agroclimatic zone of Karnataka, trees of the genus *Ficus* have been integral components of traditional rain-fed agroecosystems with field crops like millets, pulses and maize and oil seeds (Dhanya et al. 2014). *Ficus benghalensis* is the major species of *Ficus* grown in these agroforestry systems, followed *by Ficus religiosa, F. amplissima*, *F. virens*, *F. racemosa* and

Fig. 3.2 *Prosopis cineraria* in arid zones of Rajasthan, India (Photo credit: PKR Nair)

F. mysorensis var. *pubescens*. Tree management including pruning, lopping for fuel wood and harvest are usually carried out during non-cropping periods (February–April), implying seasonal division of labour and complementarity in labour utilization. Although family labour is largely used for tree management, these systems can generate alternate employment avenues. *Ficus*-based agroforestry systems provide grains, fuel wood, timber, etc. to the household. Fodder and straw are fed to livestock, which provides dairy products and farmyard manure. Birds, small mammals and insects help pest control and facilitate tree propagation (Dhanya 2011; Dhanya et al. 2012).

The ability of the species to survive under harsh conditions, cultural acceptability, multiple use benefits and ability to provide vital ecological services besides reduced dependence on external inputs are plausible explanation for farmers embracing the *Ficus* tree in dryland tracts of Mandya and Chamarajanagar districts in southern Karnataka. Analysis of litter revealed that nutrients from *Ficus* litter can potentially meet up to 76.70% N, 20.24% P and 67.76% K requirements of dryland crops annually. A socio-economic survey analysis of farmers revealed that total land holding, percentage of irrigated area, income from livestock and availability of family labour are crucial variables determining *Ficus* tree adoption in the area (Dhanya et al. 2013) (Fig. 3.3).

Fig. 3.3 *Ficus*-based agroforestry (Photo credit: B Dhanya)

2.1.1.4 Scattered Trees in Pasture Lands: *Acacia leucophloea* Silvopasture of Tamil Nadu (South India)

This system covers 100,000 ha in the dry tracts of Coimbatore and Periyar Districts where annual rain fall is around 600 mm. Although the rainfall pattern is highly erratic, *Acacia leucophloea* regenerates profusely when the land is ploughed after the first rains. Farmers encourage the growth of the young seedlings and sow crops like *Pennisetum glaucum* and *Dolichos uniflorus* (horse gram). If the rainfall distribution is normal, crops will be harvested as grain. Otherwise, they are likely to be used as fodder. At the end of the first year, roughly around 1000 or so tree seedlings remain, and this number may further deplete by natural morality to around 500–800 per ha. At the end of the third year when the trees are 1.0–1.5 m tall, tillage of soil up to the base of the trees for sowing crops is practiced (Jambulingam and Fernandes 1986).

After about 10 years when the trees are around 10 m tall and 20 cm in diameter at breast height, thinning of trees to allow a tree density between 60 and 100 per ha is done. This may be done to allow adequate sunlight to reach the understorey crops. Studies (Jambulingam and Fernandes 1986) have shown a 20–23% increase in dry-matter yield of fodder sorghum growing beneath the trees as compared to the crops grown without tree cover. The trees develop large spreading canopies when they are 15–20 years old, and farmers thin them out between 25 and 60 per ha. Such trees yield up to 100 kg of pods annually, which form an excellent high-protein fodder supplement in the dry season (Fig. 3.4).

Fig. 3.4 Scattered *Acacia leucophloea* trees in farmland at Salem, Tamil Nadu (Photo credit: S Viswanath)

Due to the uncertainty in rainfall pattern and distribution in recent times, an increasing number of farmers are now planting *Cenchrus ciliaris* grass instead of cereals and pulses. *C. ciliaris* is a hardy fodder grass, which dries up in the summer but regenerates naturally soon after the first rains. The emphasis nowadays is shifting from an agrosilvopastoral to a more predominant silvopastoral system while still giving the farmer the leeway to raise crops should conditions permit. The drought-tolerant 'Kangayam' breed of cattle developed in this area is a much coveted bull in annual bullfighting festival or 'Jallikattu' in Tamil Nadu (Jambulingam and Fernades 1986) (Fig. 3.5).

2.1.1.5 Foliage Forest 'Soppinabettas' of Malnad, Karnataka (South India)

Soppinabettas, also known as foliage forests, are minor forests allowed by Karnataka state for the areca nut farmer/grower's use as organic support in the Western Ghats area of Karnataka, South India (Nayak et al. 2000). These community-managed forests are examples of minimally managed economically valuable, high-yielding forests. Soppinabetta forests appear to be a distinct land use system that can be categorized as neither regular forests nor farmlands. The species occurring in these intensely used and managed forests are a subset of those occurring in the 'natural' forests nearby.

Oryza sativa (rice) grown on rain-fed upland fields is the major food crop of this area, where a good number of farmers still follow traditional agricultural methods. Land preparation is completed by May, before the beginning of the southwest monsoon, and the upland rice seedlings are transplanted to the fields in June after the

Fig. 3.5 Kangayam bull (Photo Credit: Senaapathy Kangayam Cattle Research Foundation)

onset of the monsoon. Many traditional varieties are cultivated. Harvest takes place in December, and an average rice yield of around 5–6 Mg ha^{-1} can be expected. Cultivation in this area largely depends on organic materials collected from adjacent Soppinabetta forests in the form of green foliage and leaf litter for compost production and certain herbs as pesticides in *Areca catechu* (betel nut) cultivation. The compost made of foliage and leaf litter from the Soppinabetta or 'foliage forests' is mixed with cow dung to produce an organic fertilizer. This fertilizer is used extensively to fertilize the betel nut farms in a completely organic mode (Purushothaman and Dharmarajan 2005) (Fig. 3.6).

2.1.1.6 Coffee Under Native Shade Trees in Coorg, Karnataka (South India)

Traditionally managed shaded coffee plantations of Coorg or Kodagu district in Karnataka contain a high proportion of native species. The high density and diversity of native trees in coffee plantations of Kodagu have been attributed to the existence of high indigenous diversity of adjacent natural forests as well as the tough forest protection laws in the district. However, farmers in Kodagu are restricted from direct marketing of their native timber by laws and public policies. As a result, many farmers prefer to plant exotic trees rather than native ones (Ambinakudige and Satish 2009).

Fig. 3.6 Soppinabettas in Malnad region paddy fields with foliage hillocks in backdrop (Photo credit: S Purushothaman and P Dharmarajan)

Most dominant species in coffee plantations of Kodagu is an exotic Australian species, *Grevillea robusta*, which commonly known as 'silver oak'. *G. robusta* in agroforestry plantations are preferred mainly because of its fast growth rate and minimal competition with robusta coffee (*Coffea robusta*). A study on growth rates of four common native timber species, viz. *Acrocarpus fraxinifolius*, *Dalbergia latifolia*, *Lagerstroemia microcarpa* and *Syzygium cumini* in comparison with the common exotic shade tree silver oak (*Grevillea robusta*) revealed some interesting statistics. *A. fraxinifolius*, as a fast-growing potential native species, could compare favourably with exotics such as silver oak, under appropriate ecological conditions (Nath et al. 2011). Ecological services of native shade trees were also superior to exotic shade trees like silver oak. Yield of coffee, consistency in yield and cupping quality of coffee beans were much improved under native shade trees (Dhanya et al. 2016) (Fig. 3.7).

2.1.2 Homegardens

Homegardening has been a way of life for centuries and is still critical to the local subsistence economy and food security (Kumar and Nair 2004) Homegardens are good replicas of native vegetation in humid tropics and help in conserving local biodiversity as well as meet the subsistence needs of local communities in a sustained manner; Tropical homegardens exist along biodiversity hotspots in Western

Fig. 3.7 Coffee grown under different shade regimes in Coorg, Karnataka (Photo credit: BN Satish)

Ghats and Eastern Ghats in India. It can also be seen in Sri Lanka; in southeast Asian regions like Java, Indonesia, and the Philippines; and in foothills of Mt. Kilimanjaro in Tanzania, Africa. The basic structure of homegardens remains almost the same across the different geographical regions. The main feature is the minimal size of individual homegarden unit, multi-storeyed canopy structure and predominance of fruit and nut trees in the upper and middle canopy levels, spice crops or root crops trailed along the woody components and understorey dominated by food or cash crops or medicinal plants (Depommier 2003).

2.1.2.1 Homegardens of Kerala

The homegardens of Kerala constitute the predominant farming systems of the state. They are small (~ 0.5 ha) and traditionally coconut-based. *Cocos nucifera* is widely used multipurpose tree species preferred in Kerala homegardens for food, energy and building materials. Homegardens are typically multi-strata systems characterized by a high density of multiple species and diversity of the woody tree components. The other main characteristic of the homegardens is their high productivity rates and diversity of production to satisfy the primary needs of the farmer, like food fuel, timber and cash. Woody perennial crops include *Areca catechu*, *Hevea brasiliensis*, *Anacardium occidentale* and *Artocarpus hirsutus*; fruit trees like *Mangifera indica*, *Artocarpus heterophyllus* and *Tamarindus indica* and many timber species such as *Tectona grandis* and *Ailanthus triphysa* are also prevalent. Legume trees like *Erythrina indica* are used to trail *Piper nigrum* (pepper vines) and *Gliricidia maculata* syn. *G. sepium* along farm boundary for meeting green manure needs (Depommier 2003) (Fig. 3.8).

Fig. 3.8 Homegarden in Kerala (Photo credit: BM Kumar)

2.1.2.2 Homegardens of Northeast India

The Barak Valley region, covering an area of 6922 km^2 located in southern Assam, is known for its homegardens. Homegardens exhibit complex structure, both vertically and horizontally. The vertical structure of homegardens is usually composed of 3–4 canopy layers: the emergent layer, the canopy, the understorey and the shrub and the herb layer. The emergent layer has a height of 15 m or more and is composed of multipurpose tree species such as *Artocarpus lakoocha*, *Bombax ceiba*, *Tamarindus indica*, *Tetrameles nudiflora* and *Toona ciliata*. The canopy layer is usually between 10 and 15 m with species such as *Areca catechu*, *Artocarpus heterophyllus*, *Mangifera indica*, *Syzygium cumini*, *Terminalia chebula* and species of bamboo. The understorey layer has a height of 5–10 m and dominated by *Citrus* spp., *Cocos nucifera* and *Litchi chinensis*. In the shrub layer of 1–5 m, species like *Hibiscus rosa-sinensis* dominate, and the herbaceous layer is mainly composed of vegetables, ornamentals and medicinal species. The shade provided in the homegardens supports many shade-loving climbers like *Piper nigrum* and root crops like *Alocasia macrorrhiza* (Das and Das 2005).

2.1.3 Bamboo in Agroforestry Practices

2.1.3.1 *Dendrocalamus stocksii* (Manga Bamboo) in Konkan Region

Dendrocalamus stocksii is naturally distributed in Central Western Ghats, in Karnataka, Goa, Kerala and Maharashtra. It is a strong, solid and thornless bamboo that can attain a height of 10 m, diameter of 2.5–6.0 cm and internodal length of

1. As a component of homestead

2. As live fencing

3. On crop field boundaries

4. As fencing around household

Fig. 3.9 *Dendrocalamus stocksii* closely integrated with farmlands in Konkan belt of Maharashtra (Photo credit: S Viswanath)

15–29 cm. Presently, it remains confined to the coastal tracts where it is cultivated in homesteads and in farm and community lands as live fences and/or block plantations. This thornless erect, solid species is now increasingly being used in furniture industry as a replacement for cane. In certain villages like Oras, Oveiye village in Sindhudurg district of Konkan belt of Maharashtra, traditionally, the entire village communities have been engaged in cultivation of this bamboo species in homesteads, as live hedges or as block plantations for centuries. Rhizome offsets of 2–3 m are typically used as new planting material which is extracted in the beginning of monsoon season in May–June and planted slanting in 0.75 m^3 pits. Mature culms of >1 year old are harvested during the dry season (Jan–May). The typical commercial length of the culms is 15–20 ft. and fetches a price of around INR 80–100, which is good revenue for the farmer. The *D. stocksii* bamboo known in Konkan belt as ‘manga’ and in Karnataka as ‘marihal’ bamboo produces 10–15 new culms annually from mature clumps (>4 yrs) and fetches the cultivator an assured annual income of a minimum of INR 1,00,000 (Rane et al. 2014; Rane et al. 2016) (Fig. 3.9).

2.1.3.2 Bamboo in Rice Paddies in Ziro Valley, Arunachal Pradesh, India

Over the last half a century or so, the indigenous Apatani tribe of Ziro Valley in Arunachal Pradesh in the Eastern Himalayan region of India has developed a unique land use system of growing rice (*Oryza sativa*) and fish together in homesteads as a viable alternative to shifting cultivation (slash-and-burn system) and as an answer to persistent shortages of food grains in the area. The 32 km^2 of cultivable land of the Ziro valley situated at an elevation of 1500 m.asl is surrounded by undulating hills of eastern Himalayas. The average farm size per family is only about 1.5 ha. In the bamboo + pine framework, the farmers integrate two types of woody perennials, bamboo (*Phyllostachys bambusoides*) and pine (*Pinus wallichiana*) (Tangjang and Nair 2015).

The system consists of growing two rice crops annually (March–July and July–October) and rearing fish in paddy fields especially during the first season. Other agriculture crops including millets are cultivated on bunds between rice fields, and domestic animals including the domesticated bison 'mithun' (*Bos frontalis*), besides pigs and poultry, are common. Only crop residues and animal waste are used to fertilize crops. Over the years, rice yield has stabilized at about 3700 kg ha^{-1} year^{-1}(two crops per year). Recently, UNESCO has added the Ziro Valley to its list of 'World Heritage Sites' in recognition of its 'extremely high productivity' and 'unique' way of preserving the ecology. The resilience and the sustainability of the system could be attributed to efficient nutrient cycling and high nutrient input through water seeping in from surrounding hills which is used to grow rice paddies (Tangjang and Nair 2015).

2.1.4 Taungya System

The Taungya system is basically an organized and systematically managed shifting cultivation. The word is reported to have originated in Myanmar (Burma), and 'tauang' means hill and 'ya' means cultivation, i.e. hill cultivation. It basically involves cultivation of crops in forests or forest trees in crop fields. The system was first introduced to Chittagong and Bengal areas in colonial era in India in1890. Later it had spread throughout Asia, Africa and Latin America. The first taungya plantations were raised in 1896 in the northeastern hill region. In southern India, the system used to be called as 'kumri'. It was usually practiced in areas with an assured annual rainfall of over 1200–1500 mm (Tewari 2008). In the initial years of the plantation establishment after clearing virgin forest lands, the labour force was encouraged to grow agricultural crops like upland rice or root crops like cassava in the interspaces to keep out weeds. But over the years due to shade effects of the forest tree crops, agriculture crop yields declined, and agroforestry was no longer possible. Though this system was highly successful in raising some of the finest teak (*Tectona grandis*) plantations in the country, it soon became unpopular due to exploitative management of the labour used for raising the 'taungya' plantations and socio-economic fallout in the aftermath (Tewari 2008).

Fig. 3.10 Taungya system – teak (*Tectona grandis*) + rice (*Oryza sativa*) (Photo credit: PKR Nair)

Essentially, the taungya system consists of growing annual agricultural crops along with the forestry species during the early years of establishment of the forestry plantation. The land belongs to the forestry departments or their large-scale lessees, who allow the subsistence farmers to raise their crops. The farmers are required to tend the forestry seedlings and, in return, retain a part or the entire agricultural produce (Nair 1993) (Fig. 3.10).

2.2 Traditional Agroforestry in Sri Lanka

2.2.1 Kandyan Forest Gardens

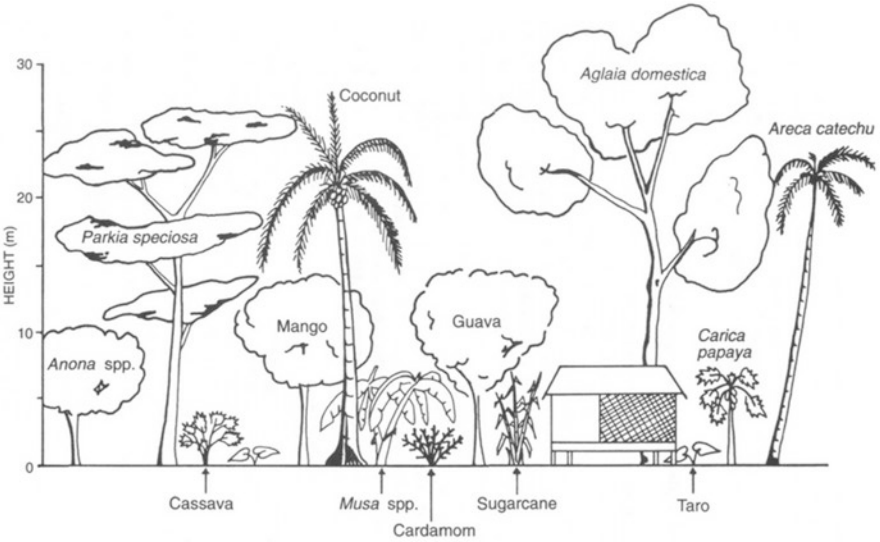
From the ground layer comprising herbaceous food, forage, medicinal and other crops to the upper canopy of fast-growing multipurpose trees, the species assembly of the Kandyan Forest Gardens (KFG) is rather distinct. The herbaceous species in ground layer varies widely from one KFG to another and is often inconsistent. The highest canopy layer (> 10 m) is dominated by *Artocarpus heterophyllus* (jackfruit) and *Cocos nucifera* (coconut). The next layer (2.5–10 m) is dominated by areca nut (*Areca catechu*) and *Gliricidia sepium*. Coffee (*Coffea* spp.) is the most dominant woody component in the third canopy layer (1–2.5 m). The four distinct vertical layers created a gradient of light and relative humidity thereby creating different ecological niches which enable diverse species to exploit them. The structured layer also contributes to soil nutrient enrichment through leaf litter and prevented soil erosion and thus afford ecological security to KFG (Perera and Rajapakshe 1991).

2.3 Traditional Agroforestry in Indonesia

2.3.1 Traditional Agroforestry in West Java

2.3.1.1 Pekarangan and Kebun-talun

The main traditional agroforestry practice in west Java, known as 'Pekarangan', is basically a homegarden intercropping system, simultaneously combining agricultural crops with tree crops and animals in housing compounds, and Kebun-talun. The latter is a rotation system of mixed garden and tree planting, sequentially combining agricultural crops with tree crops (Christanty et al. 1986) (Fig. 3.11 and Table 3.1).



Schematic presentation of the structural composition of a Javanese homegarden (pekarangan). Source: Fernandes and Nair (1986)

Fig. 3.11 Pekarangan – schematic representation (Source: Fernandes and PKR Nair 1986)

Table 3.1 Spatial and component distribution in Pekarangan homegarden

Canopy strata height	Species planted
Top layer (>10 m)	*Cocos nucifera*, *Albizia* and other trees
5–10 m layer	Fruit trees: soursop, jackfruit, duku (*Lansium domesticum*), guava, mountain apple, cloves
2–5 m layer	Bananas, papaya, other fruit trees
1–2 m layer	Ganyong (*Canna edulis*), *Xanthosoma*, beans, spinach, cassava, gembili (*Dioscorea esculenta*)
Lowest layer (< 1 m)	Taro, *Xanthosoma*, chilli pepper, eggplant

This homegarden system originated in Central Java and spread to East and West Java in the middle of the eighteenth century. In the Pekarangan, there is a mixture of annual crops, perennial crops and animals (including livestock) in the area surrounding a house. This is an integrated system with definite boundaries and serves a variety of economic, biophysical and sociocultural functions. The Pekarangan is basically identified by its five distinct canopy structure (Christanty et al. 1986).

2.3.1.2 Kebun-talun

The Kebun-talun system usually consists of three distinct stages: *Kebun* (garden), *Kebuncampuran* (mixed garden) and *talun* (mixed tree garden). The first stage, Kebun, involves clearing the forest and cultivating annual crops. These crops are generally consumed in the farm, with part of the produce sold as cash crops. In the *Kebun* stage, three vertical layers of annual crops predominate: the lowest layer consists of creeping plants that occupy the ground below a height of 30 cm. Vegetables occupy the layer from 50 cm to 1 m, and the upper layer includes maize, tobacco, cassava or leguminous vines supported on bamboo sticks. The woody perennials come into play in the later stages of the Kebun and form the mixed tree garden 'talun' (Christanty et al. 1986).

2.4 Traditional Agroforestry Systems in the Philippines

Agroforestry has been traditionally practiced by different tribal groups in the Philippines for generations. Three distinct types of traditional agroforestry, revolving around basically a homegarden, are distinguishable.

2.4.1 Multi-storey system

In this agroforestry system, mixed species occupy different canopy levels, with the upper layers occupied by trees or other woody perennials that provide partial shade to agricultural crops in the lower layers. This system is like the structure (multilayer) and composition (diverse species) of a tropical rainforest. Typical examples are coconut-coffee-pineapple-banana mix (commonly found in Cavite province), *Albizia*-coffee/cacao mix (commonly found in Mindanao province), *Gliricidia*-coffee mix (found in many dispersed areas) and homegardens (found throughout the country). This system may be also be refined by interplanting shade-tolerant species under established tree and coconut plantations (Paul Mundy 1995).

2.4.2 Rice Terraces: Forest Agroforestry System

This indigenous agroforestry system can be considered sustainable, as it has existed for more than 2000 years, and was pioneered by the Ifugao tribe in northern Philippines. A series of bench terraces is constructed along steep mountainsides, and rice is planted throughout the year. Irrigation is provided through a network of complicated canals along dikes, which originate from natural springs emanating from small forest stands called 'pinugo'. These are managed and protected by Ifugaos based on an established set of tribal laws (Paul Mundy 1995).

2.4.3 *Hanunóo Farming*

This typical farming is practiced by the indigenous Hanno communities. These communities typically build their housing structures in valleys overlooking nearby streams. The villages are small, with only 5 or 6 homes and not more than 50 people. Houses are made of wood and bamboo and have thatched roofs. The homes, which are built on stilts, are sometimes arranged in rows so that the verandahs connect to each other. The community typically grow their own food and practice 'slash-and-burn' agriculture, in which a section of forest is cut down, the plant debris burned and crops planted in the resultant clearing. In freshly cleared forest clearings, primary crops such as corn, rice, sugarcane and beans are grown, while in previously used clearings, secondary crops such as sweet potatoes are cultivated. Sometimes bananas and papayas are also grown in older clearings. After repeated cultivation, the clearings are left fallow and may not be used again before the next two years at least. In addition to farming, domestic animals are maintained to provide dairy products, and animals are slaughtered only during festive occasions (Conklin 1957).

2.5 Traditional AF in Japan

2.5.1 Satoyama

Satoyama is a traditional agricultural landscape in Japan comprising of several habitat types, including paddy fields, secondary forests, secondary grasslands, ponds and streams in sequence from top to bottom of the hill. The variety of habitats and connectivity among them have contributed to the high species diversity within *satoyama* (Katoh et al. 2009). The satoyama is characterized by multifunctionality, in which social and economic dimensions rather than ecological dimensions dominate. Satoyama has the potential to supply important ecosystem services, including the preservation of important cultural heritage, biodiversity conservation and education. Satoyama landscapes, like other systems, are based on indigenous knowledge around the world. These landscapes have suffered a period of decline and lack of recognition. Currently, efforts are being used to revive and conserve these systems and the indigenous knowledge and cultural heritage they represent. Satoyama is thought to be harbinger of biological diversity and has the potential to serve as 'carbon forests'. There are also structural and functional differences (nature, complexity and objectives) between agroforestry and satoyama. While agroforestry involves more than one life form on the same land management unit with key productive and protective functions in an intensive management mode, the satoyama woodlands are extensively managed, and understorey production is seldom an objective (Kumar and Takeuchi 2009).

3 Traditional Agroforestry Systems in Europe

3.1 Dehesa

This is another very old system (>4500 years) found in the Mediterranean zone and may be considered as the most widely used agroforestry system in Europe. This peculiar agroforestry system dominates the landscape of the southwestern Iberian Peninsula. The system is characterized by the presence of a savannah-like open tree layer, mainly dominated by Mediterranean evergreen oaks – Holm oak (*Quercus ilex*) and cork oak (*Q. suber*) – and to a lesser extent by the deciduous *Q. pyrenaica* and *Q. faginea*. In Spain, this system is known as 'Dehesa', while in adjacent Portugal it is known as 'Montado'. This is a man-made ecosystem, and its two-layered structure, tree and grass, is dependent on human practices and management. Some characteristics, particularly tree density, seem partly controlled by edaphic and climatic resources. This traditional system is highly diversified in terms of livestock types (sheep, goats, Iberian pigs, and cattle). In recent times, the grazing of the high value Iberian pig has been the most profitable component of the system (Joffre et al. 1999).

The herbaceous layer is comprised of either cultivated cereals (oats, barley, wheat) or, more commonly, native vegetation dominated by annual species, which are used as grazing resources. Control of invasive matorral shrub species, *Cistus ladaniferus*, *C. salviifolius* and *C. monspeliensis*, has been traditionally managed by two complementary aspects, i.e. manual uprooting of the matorral shrub species in the central areas followed by the clearing and ploughing of peripheral areas by landless peasants possessing a plough horse. In exchange for the invested labour, the land owner would give the peasants permission to cultivate cereal crops on the newly reclaimed land and a share in the charcoal produced from the cleared vegetation. The Dehesa and Montado systems are excellent examples of productive land use by way of continuous transfer of nutrients from woodland to cultivated land through animal manure (Joffre et al. 1999).

3.2 Pré-verger and Streuobest

In many countries of Europe like England, France and Germany, growing of fruit trees in arable lands or pasture lands had evolved over a period and used to be referred as pré-verger or Streuobst in its native country. The involvement of grazing animals and the practice of orchard intercropping can be traced back to the Roman Empire era. At that time, olive trees were predominantly intercropped with wheat (*Triticum sativum*) in alternate years. In the seventeenth century, orchards in England were also intercropped with wheat. In France, the term pré-verger mainly describes low-density (40–80 trees ha^{-1}) plantations of fruit trees on grassland. Beside fruit trees such as apples (*Malus* spp.) and pears (*Pyrus* spp.), the trees are expected to yield timber as a by-product (Nerlich et al. 2013).

In temperate Europe, fruit trees were traditionally grown on agricultural land or managed grasslands in a system referred to as Streuobst. Quite like pré-verger, the Streuobst consists of fruit trees scattered on agricultural land with densities ranging from 20–100 trees ha^{-1}. This land use system complements the meagre food supply and offers a platform for commercial fruit production. The refinement of this land use system started in the fifteenth and sixteenth centuries when fruit trees were propagated in the open landscape outside homegardens and orchards came to be regarded to showcase prestige and affluence of the moneyed (Nerlich et al. 2013). Streuobst was common until the 1950s, but with progressive mechanization and the increasing cost of manpower and cheap fruit imports, the traditional structures have become increasingly uneconomic. Most Streuobst systems have since been replaced by intensively managed short cultivars. In the last 40 years, the number of Streuobst trees has declined by 50% in southwestern Germany where the system was previously common (Nerlich et al. 2013).

3.3 Hauberg

This another specialized traditional agroforestry practice that originated in northwestern Germany in the middle ages. Initially started off as a form of low forest consisting predominantly of oak and birch to provide wood and charcoal to communities and after extracting the timber, the areas were burned to release nutrients to fertilize the soil. Cereals are then grown for several years, followed by a longer fallow under pastoral use till new regeneration of forest could be established after a rotation of around 20 years. The Siegerland area, where Hauberg is seen, was earlier known for its ore deposits. But the extraction process of ore required considerable amounts of charcoal, and standing forests were chopped for this purpose. Hauberg was then developed as a sustainable cropping system to compensate for extensive deforestation. Several of the traditional agroforestry practices referred to in previous sections still exist in Europe, although their use has considerably declined (Nerlich et al. 2013).

3.4 Chania System of Greece

This land use system is prevalent in Greece and other parts of southeastern Europe. The main feature of this land use system is the intercropping of cereals with fruit trees. Fruit trees found in this system are usually *Olea europaea*, *Castanea sativa*, *Juglans regia*, etc. The animal component in some form of silvopastoral system involving goats and cattle may also be noticed. This used to be a widespread practice since first millennium BC. Leaf and twigs lopped from the trees are used as animal fodder especially during winter. Tree fodder and hay from intercropped cereals helped livestock survive during winter month, while fruits, cereals and animal products helped communities to tide over harsh winter. The Chania system has been a part of traditional way of life and has a rich cultural history in Greece (Papanastasis et al. 2009).

4 Traditional Agroforestry Systems in Africa

4.1 Kihamba Sytem or Chagga Homegardens in Tanzania

Inhabitants of the highlands in Mount Kilimanjaro region have traditionally developed and refined a unique farming system well suited to local conditions known as the Chagga homegarden or Kihamba system. It is believed that the first homegardens and traditional water canals existed even in the twelfth century A.D. This old land use system has formed the identity of the local Chagga communities, who are of multi-ethnic origin (Fig. 3.12).

In the Chagga homegardens, typically, four distinct vegetation layers are seen. The upper strata tree layer provides shade, firewood and farm construction wood. Below this tree layer, some fodder crops, medicinal value plants and bananas are grown. The next stratum is comprised of bananas below which coffee bushes are maintained, and further below vegetables are cultivated. This multilayer system maximizes the use of limited land in Chagga homegardens. The entire area is irrigated through a well-established network of canals fed by main furrows originating from the montane forest above in Mt. Kilimanjaro. Multilayered vegetation structure of Chagga homegardens is very like the structure of a tropical montane forest with the growth form spectrum displaying a myriad of trees, shrubs, herbs, lianas and epiphytes.

Fig. 3.12 Chagga homegardens of Mount Kilimanjaro (Photo credit: CK Kunhamu)

Apart from some cultivated fruit trees like avocado, mango or introduced timber trees such as *Grevillea robusta* and *Cupressus lusitanica*, most of the 82 odd tree species encountered in Chagga are remnants of the previous forest cover. Some of the common forest trees noticed in Chagga homegardens include *Albizia schimperiana*, *Cordia africana*, *Commiphora eminii and Margaritaria discoidea* (Hemp and Hemp 2008). An open light upper canopy is formed by *Albizia schimperiana* var. *amaniensis*, on which epiphytes such as the fern *Drynaria volkensii* and *Telfairia pedata*, a liana with oil-yielding seeds also known as oyster nut, find a niche habitat.

4.2 Matengo Ngoro Pit System

The Matengo people are obliged to stay only on the upper areas of mountains because of conflict with the Ngoni people living below in the plains. Due to high population pressure coupled with limited land resource, the Matengo people were compelled to increase yield per unit area to sustain themselves. To overcome these constraints and to eke out survival in the highlands, the Matengo evolved an intensified cultivation system, known as ‘Ngoro’, with unique soil conservation features to augment food production. Literally translated, Ngoro means ‘pit’ in the Matengo language. Since a Ngoro field has many pits, the system has come to be referred to ‘Matengo Ngoro-pit cultivation’ (Aichi et al. 2013).

There is a clear division of labour in the tribal community while managing this system. The native vegetation in the plots is slashed and cleared by males in the tribe. The grass and crop residues are left to dry for about 2–3 weeks in square-shaped lines of about 2 m by 2 m size. The women then join to dig the pits in the designated area. The soil is dug in the middle of the pit to cover the grasses forming a series of ridges with pits in the middle in a honeycomb lattice like structure. Beans, wheat, finger millet, cowpeas and maize are grown on the ridges surrounding the pits (Aichi et al. 2013).

4.3 Ngitili Agroforestry System in Western Tanzania

The Ngitili is a traditional silvopastoral pastoral system of the Sukuma tribe in western Tanzania, especially in Shinyanga region of West Tanzania. The Ngitili silvopastoral system comprises livestock and trees/vegetation components, both of which are managed together to generate socio-economic and environmental benefits. Under the Ngitili, communities set apart grazing areas to serve as a reserve for supplying fodder during the dry season when supply is limited. The Ngitili also provides wood and non-wood products, medicines and food to the households. The Ngitilis concept is based on conservation of natural resources for food security, besides supply of wood and non-wood resources for other household needs. Ngitilis comprise trees forming the upper layer while grasses mixed with forbs form the other lower layers. A great diversity in composition as well as size of Ngitilis may be seen from district to district depending on land availability, usage and climatic differences. Dominant tree species found on Ngitilis include *Acacia tanganyikensis*, *Acacia polyacantha*, *Afzelia quanzensis*, *Brachystegia* spp., *Commiphora africana*, *Combretum zeyheri* and *Dalbergia melanoxylon* (Aichi et al. 2013). The system is managed through careful grazing resource management and crop husbandry practices controlled and monitored by village by-laws, which are enforced by the 'Sungusungu' or community police (Aichi et al. 2013) (Fig. 3.13).

4.4 Parkland System of West Africa

In the Sahelian zone of West Africa, crops grown under a discontinuous stretch of scattered trees dominate many landscapes which constitute the parklands. They are the predominant agroforestry system in semiarid West Africa. The parkland system reflects the ecological knowledge of the farmers in risk prone environment. This method of cultivation prevents soil erosion and may even help to mitigate the adverse effects of climate change (Bayala et al. 2014) (Fig. 3.14).

Despite the benefits accruing from firewood, medicine, food and fodder, parklands are facing destruction because immense livestock pressure. Shortened periods of fallow and severe tree lopping for livestock feed and firewood have however started to affect the sustainability of these systems (Bayala et al. 2014). Classification

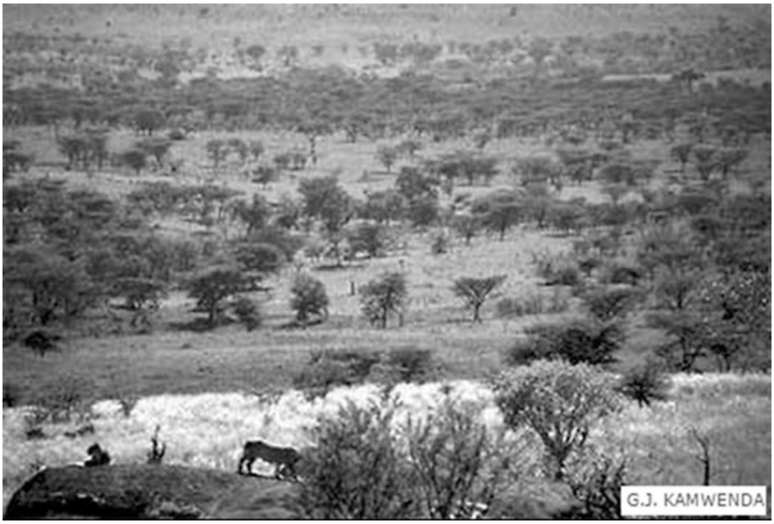


Fig. 3.13 Typical Ngitili, Shinyanga region, United Republic of Tanzania. (Photo credit: GJ Kamwenda)

Fig. 3.14 *Faidherbia albida* trees intercropped with maize (Tanzania) (Photo credit: PKR Nair)

of parklands in relation to the degree of human intervention that contributed to their formation has proved useful in revealing gradations of management intensity and thereby giving parklands a broad, inclusive representation in human-dominated vegetation types.

The 'selected' parklands dominated by karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) play an important role in serving various human needs of food, fodder or soil fertility. The slow growth rate of *Vitellaria paradoxa* imparts these parklands with a certain degree of permanence. *Borassus aethiopum* and *Elaeis guineensis* are other important trees which sustain the productivity of these 'selected' parkland systems (Boffa 2001).The 'constructed' parkland type is composed of trees species which are protected, pruned and tended to reach large height and crown dimensions. *F. albida*-dominated parklands are an excellent example of this category. This species is inherently bushy but develops as tall trees when pruned earlier on. This type has also been called 'substitution parkland' because *F. albida*, though absent in climax communities, may partially or completely replace spontaneous vegetation (Boffa 2001).

The lack of clear definitional boundaries tends to make the different parkland types less functional than desired. Very often 'selected' and 'constructed' parklands can overlap as in the case of *Vitellaria* and *Parkia* parklands. Both are selected from the pre-existing vegetation, but they are also constructed through community management. Tree size and relative abundance are greatly enhanced through the selective process, and their density in parklands may be increased through fallow enrichment, transplanting or planting. As parkland trees become more valuable, management becomes more intensive through manuring, trimming and pruning practices. Then, in the future, probably the distinction between selected and constructed parklands may become less pronounced.

5 Traditional Agroforestry Systems in South America

5.1 AFS in the Amazon Brazil

Agroforestry practices in this area are widespread and extremely varied. Four distinct systems are found in Amazonian belt, all of which begin as shifting cultivation fields but differ greatly in species composition and richness, intensity and length of management, economic orientation and adaptation to ecological conditions. The first system resembling 'Swidden fallow agroforestry' is popular among the Bora Indians. This involves the concurrent use of many adjacent plots used for sustaining a variety of annual, semi-perennial and perennial crops. All stages starting from early swidden to mature forest fallow can be seen. The second system is of a market-orientated agroforestry in Tamshiyacu, carried out by Riberenos (the majority population of the Peruvian Amazon, descended from natives and immigrants) who cultivate pineapples and Umari (*Poraquei basericea*) fruit as principal cash crop within a swidden fallow system. The third system is characterized by diverse orchard fallows seen in Santa Rosa (a mestizo, i.e. non-Indian area, but populated by descendants of tribal groups and of families of Caucasian origin). This system combines characteristics of the first two systems and has both ordinary swidden plots and agroforestry plots typical of the region. A large number and variety of cultivated fruit trees are maintained over a considerable period. The fourth agroforestry system, which is popular in the Varzea village of Yanallpa, has only recently been studied and documented. The higher natural levee area where the village is situated is occasionally flooded by the Amazon River. This area is dominated by permanent multi-species orchards, interspersed with maize, plantains and *Manihot esculenta* (manioc or cassava). The lower levees in the flood plains, which are inundated every year, are planted regularly with annual food crops (Padoch and Jong 1987).

Agroforestry system in Northeast Brazil covers a vast land area and is mostly semiarid. The rainfall varies widely from 300 to 1000 mm/yr. This region has a long tradition of grazing under plantations. These are silvopastoral systems of grazing under tree crops such as cashew, coconut and carnauba palm (*Copernicia prunifera*). The common fodder grasses seen in this area include ginger grass (*Paspalum maritimum*) and African guinea grass (*Panicum maximum*) (Johnson and Nair 1985).

Amazonian systems – This system is practiced in the vast Amazonian humid tropical lowlands region of South America (Brazil, Peru, Colombia, Venezuela, Guyana, etc.). The major components in this traditional agroforestry system are fruit trees and various palms and cacao and also various timber trees and Brazil nut (*Bertholesia excelsa*) and agricultural crops like cassava, yams, beans, plantains, etc. Fruit trees and other trees planted around the house and seedlings of these are usually grown in house gardens. Seeds of fruit trees are interplanted with agricultural crop. Multiple outputs from a variety of trees, palms, shrubs and food crops offer nutritional security and cash income and also help in biodiversity conservation by acting as a repository of indigenous strains and varieties of numerous economically useful plants (Miller and Nair 2006).

6 Traditional Agroforestry Systems: North America

6.1 The Quezungual System: An Indigenous Agroforestry System of Honduras

The Quezungual system is an indigenous system practiced by small holder farmers in Lempira area of western Honduras. In this system, naturally regenerated trees of different kinds and even shrubs are pollarded to a height of approximately 1.5 m. Trees are pollarded in the dry season to reduce the risk of pests and diseases. The pollarded material is often left to dry on the surface of the soil. At the beginning of the rains, farmers sow agricultural crops through the dead pollarded material spread out in the field. These pollarded trees coexist with taller trees in the fields such as *Cordia alliodora* (laurel) and other fruit trees like *Psidium guajava* (guava), *Citrus* spp. (mandarin orange), *Persea americana* (avocado) and *Mangifera indica* (mango). Multiple food and pulse crops like *Zea mays* (maize), *Sorghum bicolor* (sorghum) and *Phaseolus vulgaris* (beans) are grown in these fields. The main highlight of the system is its propensity to retain soil moisture besides production of fruits and timber. Additionally, the plots can be cultivated for longer periods than usually seen in other parts of the country. The usual practice of controlled burning before the advent of the rains in April is not seen in this system.

Farmers manage the Quezungual system in such a way to ensure that there is optimum shade for the agricultural crops. The density of the trees and shrubs is optimally managed, and tree species are pollarded when crops are sown in the beginning of the cropping season and subsequently pruned towards the end of the season. Many of the farmers do not have any title of their land, and in many cases, per hectare holding size is less than 2.5 ha land and that too in mostly steep terrain (5–50% slope). The direct benefits accrued to small holder farmers have made this system popular in Honduras (Hellin et al. 1999).

7 Traditional AF system: South Pacific Islands

Pacific Islands are lowland humid tropics having well-distributed rainfall of >1500 mm per year. Traditional agroforestry system in the Pacific Islands is dominated by specialty crops and trees. The structure of these systems is characterized by the presence of various tropical fruit and nut trees in the upper storey like *Cocos nucifera*, *Albizia saman*, *Albizia lebbeck*, *Ceiba pentandra and Bischofia javanica* and shorter trees in second storey like the Pacific litchi (*Pometia pinnata*), candlenut tree (*Aleurites moluccana*) and beach hibiscus (*Hibiscus tiliaceus*). Tuber crops dominate in the lowest storey like taro (*Colocasia esculenta)* and sweet yams *(Dioscorea esculenta)*, with ornamentals like common hibiscus (*Hibiscus rosa-sinensis*), ylang ylang *(Cananga odorata)* and hedge panax *(Polyscias guilfoylei)* are seen along the farm boundary.

Upper storey fruit trees are pruned to allow sunlight for lower storey species. The under storey is allowed to return to fallow for a period ranging from 4 to 10 years, retaining only fruit trees. Tree products like fruits, vegetables, small timber, fibre, flowers for decoration and ornamentation and products like food, medicine and beverages are obtained from this system. Complementary sharing of growth resources can be visualized in the system. The trees also provide protection from erosion, wind and salt spray. Other benefits include production of kava, a social beverage drink, and tapa cloth from paper mulberry (*Broussonetia papyrifera*). The high diversity of woody species ensures maximum utilization of natural resources in this multi-strata system (Elevitch 2011).

8 Conclusions

Agroforestry systems may include both traditional and modern land use systems wherein trees are managed together with crops and/or animal production systems in agricultural landscapes. Under ideal conditions agroforestry combines the best practices of growing trees and managing agricultural systems resulting in profitable and most sustainable land use systems. Traditional agroforestry systems are essentially highly region specific and, in many instances, have evolved over time as a response to specific threats or needs like the Parkland system of West Africa or the Matengo Ngoro pit system. Among the homegardens, the Chagga homegardens of Tanzania or *Pekarangan* and *Kebun-talun* of Indonesia or the homegardens of Kerala or Kandyan Forest Gardens of Sri Lanka have all clearly tried to mimic the adjoining natural forests, thereby imparting in-built ecological resilience besides addressing the food security needs of the household. The traditional agroforestry systems in the Mediterranean and Europe have a lot of emphasis on fruit- and nut-yielding trees with an intrinsic animal component in varying degrees of management as a response to sociocultural sensibilities. A recent qualitative analysis of some of the prominent traditional agroforestry systems (Nair et al. 2016) using a SWOT (strengths–weaknesses–opportunities–threats) analysis approach showed several commonalities among them with sustainability, multifunctionality and sociocultural values emerging as common strengths, while low levels of production and lack of research and technology inputs were projected as the major weaknesses. The stability and longevity of the TFS also appear to be dependent on the respective government policies. Undoubtedly, a long-term vision which promotes nutritional security, sustains livelihoods, alleviates poverty and promotes resilient agriculture production systems should take some cues from TFS. Perhaps with more studies and more robust research data emerging on soil carbon sequestration, provisioning and non-provisioning services of TFS, these systems may see resurgence in the coming foreseeable future. Then perhaps, the lessons learnt in managing TFS can better equip agricultural landscapes to mitigate vagaries of climate change.

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Chapter 4
Utilizing Geospatial Technologies for Agroforestry Research and Development in India

R. H. Rizvi, O. P. Chaturvedi, and Ram Newaj

Abstract Geospatial technologies like GIS, GPS and satellite remote sensing have wide applications in crop area estimation, forest cover assessment, management of natural resources, watershed planning and monitoring, disaster assessment, etc. These technologies can be successfully applied in agroforestry research and development in India. Some of the fields of agroforestry research are estimation of agroforestry area in the country, assessment of carbon stock/sequestration under agroforestry systems, development of library of spectral signature for identification of tree species on farms and development of spatial decision support systems (SDSS) for selection of suitable agroforestry species/systems for a particular area. This chapter has highlighted recent developments in these research areas of agroforestry. Methodology for estimating area under agroforestry using remote sensing and some country-level estimates are given. Utilization of the geospatial technologies in assessment of carbon sequestration under agroforestry systems is also described. Some methods of tree species identification on farms have been demonstrated in this chapter.

Keywords Geospatial technologies · Management of natural resources · Decision support systems · Carbon sequestration

1 Introduction

Agroforestry is a land use that involves deliberate retention, introduction or mixture of trees or other woody perennials in crop/animal production field to benefit from the resultant ecological and environmental interactions. Agroforestry is identified as an alternate land use technology towards restoration of ecosystems by reclamation of degraded soils/lands; conservation of soil, water and environment; livelihood

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security; and mitigation of climate change. The role of agroforestry in carbon storage and tapping atmospheric CO_2 in the form of standing biomass (above and below ground) is yet to be quantified for different agro-climates. However, the potential of agroforestry for resource conservation, rehabilitation of degraded lands and improvement of environmental quality has been clearly demonstrated (Dhyani et al. 2005; Dagar et al. 2014), and also potential for agroforestry exists in fallow lands (NRCAF 2007).

In India, the diagnostic survey and appraisal of agroforestry practices in the country revealed that there are enumerable practices in different agroecological zones (Pathak et al. 2000). These systems/practices occupy sizeable areas. Though an effort has been made by Dhyani et al. (2013) to estimate the agroforestry area in the country, however, these estimates are not the true reflection as they are not based on ground truthing. Some estimates of area and production of wood for the tree cover outside forests are available (FSI 2013), but these estimates include trees on canal side, on roadside and in urban areas and thus do not represent true agroforestry area. The accurate assessment of the area under agroforestry systems in different agroclimatic regions of India can be done with the help of geospatial technologies. Nair et al. (2009) estimated globally 823 million hectare (M ha) area under agroforestry and silvopastoral systems, of these 307 M ha is under agroforestry. However, these estimates come from taking the FAO estimate of agricultural land multiplied by an estimate of 20% covered by agroforestry. But this value of 20% is not based on objectively measured data. Zomer et al. (2009) find agroforestry widespread with almost half of the world's agricultural lands having at least 10% tree cover. Manual (traditional) methods of mapping take a relatively long time and high cost.

The integrated use of spatial technologies like Geographical Information System (GIS), Remote Sensing (RS) and Geographical Positioning System (GPS) has the potential to overcome the above constraints. GIS enables the storage, management and analysis of large quantities of spatially distributed data (De Mers 1997). The integration of satellite remote sensing data into GIS is one of those great ideas which have made valuable contribution in other fields but need to be utilized in this area. Furthermore, remote sensing is often the most cost-effective source of information for updating a GIS, and it is a valuable source of current land use/land cover data (Campbell 1996; Star et al. 1997). Remote sensing techniques have been utilized successfully in certain areas of application, including forestry, watershed management, agriculture and related fields, especially in developed countries where agriculture patterns are well defined and methodologies developed. In agroforestry, however, these technologies have yet to be used extensively (Ellis et al. 2000).

The applications of spatial technologies enable the storage, management and analysis of large quantities of spatially distributed data. These data are associated with their respective geographic features. For example, in agroforestry, the type of tree species and associated crops would be related with a sampling site, represented by a point. Data on existing agroforestry systems and area dwelt in might be associated with fields or experimental plots, represented on a map by polygons. The power of GIS lies in its ability to analyse relationship between features and associated data (Samson 1995). Satellite images are used to identify what is growing, while GIS component is used to assess area, categorize it and locate its position on earth's surface to provide complete record of the site.

2 Applications of Geospatial Technologies in Agroforestry Research

Multipurpose Tree and Shrub (MPTS) database version 1.0 contained information for 1093 species including site-specific requirements (e.g. soils), morphological and phonological descriptions, management characteristics and environmental responses (Schroder and Jaenicke 1994). In a spatial database approach, suitable areas for agroforestry were estimated in sub-Saharan Africa (Unruh and Lefebvre 1995), and suitable areas of *Annona cherimola* agroforestry system were determined in Southern Ecuador (Bydekerke et al. 1998). The role of GIS in the characterization and monitoring of agroforestry parks was also highlighted by Bernard and Depommier (1997). Paquette and Domon (1997) did spatial analysis of census and geomorphologic data in GIS environment to explore dynamics of agroforestry in nineteenth-century Canadian landscape. In India, the agroforestry database (*Agroforestry BASE*) has been developed containing information on various aspects of agroforestry under independent modules/databases, namely, MPTS, economic analysis and agroforestry intervention/innovations (Ajit et al. 2003). Bentrup and Leininger (2002) did suitability assessment using GIS to determine the best locations for growing agroforestry specialty products. Suitability assessment matches potential products with ideal growing conditions. Acosta and Reyes (2002) developed a geographic information system for identification of areas suitable for development of silvopastoral systems in the region of Jimaguayú in the provenance of Camaguey in Cuba. An assessment of the current status of the West African agroforestry parklands was launched in 2002 by ICRAF. Zomer et al. (2007) in his study used a simple water balance approach, combined with the results of a remote sensing analysis of tree cover in the study area, to estimate the impacts of poplar agroforestry on hydrological cycles at the farm to regional scale.

A geospatial analysis of remote sensing-derived global datasets investigated the correspondence and relationship of tree cover, population density and climatic conditions within agricultural land at 1 km resolution. There are limitations in this analysis that one cannot expect results for an individual pixel (1 km × 1 km) to be close to reality. Also at landscape scale, the correlation between tree cover and % crown cover is probably quite good within broad agroforestry systems and climate zones, but this will not be true globally (Zomer et al. 2009). Agroforestry, if defined by tree cover on agricultural land of greater than 10%, is found on more than 43% of all agricultural lands globally. This land use type represents over one billion ha of land and more than 900 million people (Zomer et al. 2014).

3 Agroforestry Mapping by Remote Sensing Technique

A major problem in estimating area under agroforestry is lack of procedures for delineating the area influenced by trees in a mixed stand of trees and crops. In simultaneous systems, the entire area occupied by multi-strata systems such as homegardens, shaded perennial systems and intensive tree-intercropping situations can be listed as agroforestry. The problem is more difficult in the case of practices such as windbreaks and boundary planting where trees are planted at wide distance between rows (windbreak) or around agricultural fields (boundary planting) because the influence of trees extends over a larger than easily perceivable extent of areas (Nair et al. 2009). Rizvi et al. (2009) estimated area under agroforestry systems in Yamunanagar district using Resourcesat-1 LISS-III data, which come out to be 18.4% in year 2007. Rizvi et al. (2011) reported an estimated area of 11.3% under agroforestry systems in Saharanpur district. They also reported that there was a decline in area under agroforestry over a period of 10 years from 1998 to 2007. Rizvi et al. (2013) highlighted some issues in mapping agroforestry like spatial resolution, spectral resolution, time period of remote sensing data and methods to be used.

Some estimates of area and production of wood for the tree cover outside forests are available (FSI 2013), but these estimates also include trees on canal side, on roadside and in urban areas and thus do not represent true agroforestry area. Kumar et al. (2011) mapped trees outside forests using merged data products of LISS-IV and Cartosat-1 and found 11.09% area under trees outside forest in Bilaspur block of Yamunanagar (Haryana). Tauqeer et al. (2016) mapped *Populus*- and *Eucalyptus*-based agroforestry systems in Ludhiana district using LISS-IV multispectral data. Extensive survey was also performed for ground truthing. Scattered trees on farmlands and boundary plantations are difficult to identify with medium-resolution satellite data like LISS III (23.5 m) or Landsat (30 m). For correct estimation of area under scattered trees, high-resolution multispectral data either LISS IV (5.8 m) or merged LISS IV and Cartosat-1 datasets must be used. But this would involve enormous data processing, and huge cost as far as regional- or country-level mapping is concerned.

3.1 Methodology Developed for Agroforestry Mapping

The following methodology given by Rizvi et al. (2016a) may be adopted for mapping and estimating agroforestry area at district level, which is depicted in Fig. 4.1.

Medium-resolution remote sensing data (LISS III, 23.5 m) has been used for mapping agroforestry at district level. Preprocessing of remote sensing images includes layer stacking, mosaicking and subsetting with district boundary. Maximum likelihood method of supervised classification was applied for land uses and land

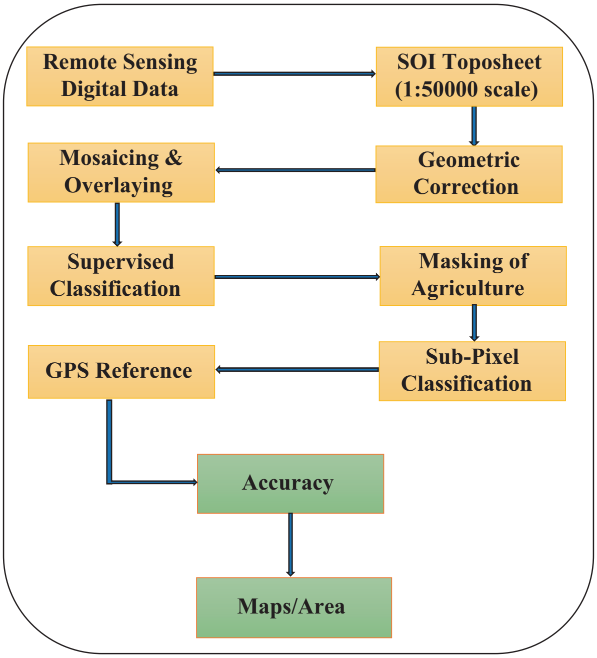

Fig. 4.1 Flowchart of methodology for estimating agroforestry area at district-level

covers in a district using ERDAS Professional ver. 11.0 software. District area has been classified into nine classes, viz. cropland, grassland, wasteland, plantation, agroforestry, forest, built-up areas, water bodies and sandy area. Such pixel-based methods account for single major feature occurring in a pixel, even if more than one feature/land cover is present. Besides, some wrong classification may happen with pixel-based methods (Fig. 4.2). Therefore, subpixel method of classification was applied on agricultural land because agroforestry exists on agricultural land only.

Agricultural land including cropland and fallow land was masked from false colour composite (FCC) of the districts. Then subpixel classifier is applied on this agricultural area. Resultant image will consist of (i) pixels covering trees plus cropland, (ii) pixels covering fallow land plus trees, (iii) pixels covering trees only, (iv) pixels covering cropland only and (v) pixels covering fallow land only. Pixels of first three categories will represent agroforestry in real sense, and their total area would give an estimate of area under agroforestry. Advantage of using subpixel classifier is that this method not only overcomes the problem of intermingling of sugarcane with young plantations but also gives outcome in the form of per cent tree cover within pixel. This tree cover ranges from minimum 20 to maximum 100%, thus accounting for single tree, boundary plantations and block plantations on farmlands (Fig. 4.3).

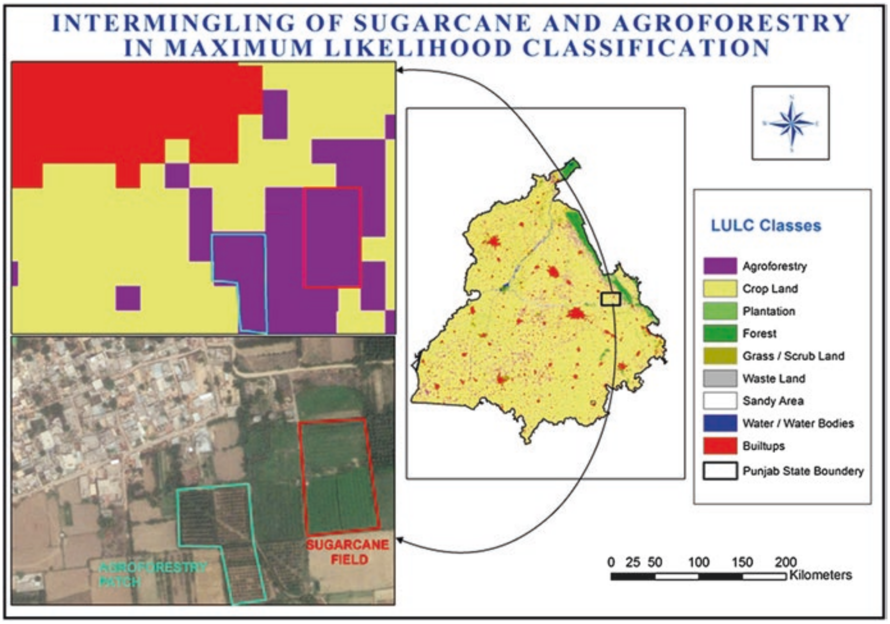

Fig. 4.2 Intermingling of sugarcane and agroforestry in maximum likelihood classifier

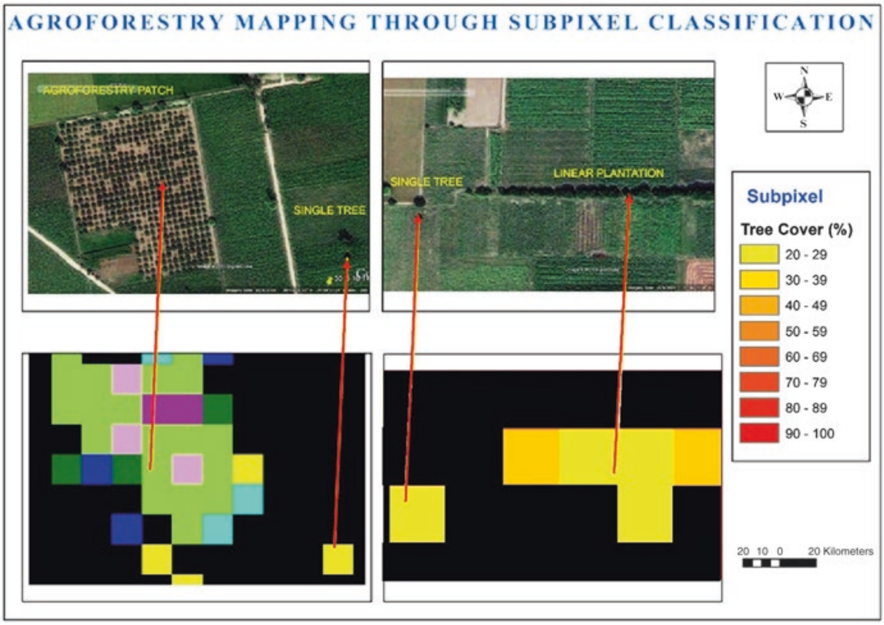

Fig. 4.3 Single tree, linear plantation and block plantations identified through subpixel

3.2 Estimation of Agroforestry Area at Zone Level

For mapping and estimating of area under agroforestry, the following approach has been adopted:

1. From each agroclimatic zone, 20% of districts representing that zone will be randomly selected.
2. For each district, remote sensing data will be analysed for land uses and land covers (LULC) by maximum likelihood classification method.
3. With the help of this LULC, agricultural land (cropland + fallow land) will be clipped because agroforestry exists on agricultural land only.
4. Then subpixel classifier will be applied on this agricultural area, which gives output in the form of tree cover classes (20–30, 30–39, ….………, 90–100%) within a pixel.
5. Agroforestry area obtained for such 20% of selected districts in a particular agroclimatic zone will be extrapolated for entire zone.
6. Cumulative sum of area under agroforestry for all agroclimatic zones will give an estimate of area under agroforestry for the country.

3.3 Country-Level Estimates of Agroforestry Area

Dhyani et al. (2013) estimated the agroforestry area as 25.32 M ha or 8.2%t of the total geographical area of the country. As such, an average of 14.2% of total cultivated land has agroforestry in one form or the other. However, these estimates are not the true reflection as they are not based on ground verification or revenue records. They have also projected the agroforestry area for year 2050 at 53.32 M ha. As per FSI (2013) estimates of green tree cover under agroforestry, 11.15 M ha area was found. For agroforestry, only rural TOF has been taken into consideration, and tree green cover was estimated for 14 physiographic zones of India. But, only block and scattered stratum are accounted and not linear stratum which is also a part of agroforestry. There is a difference in tree cover estimates (91,266 km^2) and tree green cover under agroforestry (111,554 km^2); tree cover includes both urban TOF and rural TOF. Rizvi et al. (2014) gave preliminary estimates for extent of agroforestry area in India by using Bhuvan LULC data (http://bhuvan-noeda.nrsc.gov.in/theme/thematic/ theme.php) for the year 2011–2012 (Table 4.1).

These estimates have been worked out by considering minimum 10% of agricultural land having agroforestry. According to this, there is about 14.46 M ha area under agroforestry when fallow lands are not included, and potential area under agroforestry is estimated to be 17.45 M ha when fallow lands are included. Presently,

Table 4.1 Preliminary estimates of agroforestry area in India (Figures in ‘000 ha)

State/UT	Cropland	Fallow land	AF area (excluding fallow)	AF area (including fallow)
Andhra Pradesh	11,752	4983	1175	1673
Arunachal Pradesh	176	6	18	18
Assam	2590	81	259	267
Bihar	7565	385	756	795
Chhattisgarh	6007	990	601	699
Delhi	49	8	5	6
Goa	93	17	9	11
Gujarat	8126	2771	813	1089
Haryana	3359	158	336	352
Himachal Pradesh	327	–	33	–
J & K	883	53	88	94
Jharkhand	2932	2404	293	534
Karnataka	9242	3694	924	1293
Kerala	860	83	86	0.94
Madhya Pradesh	11,724	1727	1172	1345
Maharashtra	16,067	3095	1607	1916
Meghalaya	219	–	22	–
Manipur	182	–	18	–
Mizoram	40	–	4	–
Nagaland	47	1	5	5
Orissa	5649	2391	565	84
Puducherry	12	5	1	2
Punjab	4130	73	413	420
Rajasthan	15,511	5001	1551	2051
Sikkim	68	11	7	8
Tripura	256	3	26	26
Tamil Nadu	6499	382	650	688
Uttar Pradesh	18,641	1071	1864	1971
Uttarakhand	706	39	71	74
West Bengal	3600	456	360	405
All India	*144,588*	*29,895*	*14,459*	*17,448*

Source: Rizvi et al. (2014)

under National Initiative on Climate Resilient Agriculture (NICRA) project, area under agroforestry systems in different agroclimatic zones of India is being estimated using same methodology discussed in section 3.2. So far, ten agroclimatic zones have been completed, and agroforestry area in these zones has been estimated to be 16.60 M ha. Once all 15 agroclimatic zones are completed, then actual figure of agroforestry area will be obtained.

4 Identification of Tree Species on Farmlands

*4.1 Sapota (*Achras zapota*) based Agroforestry in Junagarh District*

In Junagarh district, fruit as well as timber species were found under agroforestry. Sapota (*Achras zapota*) and mango (*Mangifera indica*) were the dominant species among them. For species-level classification, agroforestry area already obtained by subpixel classifier was again used (Fig. 4.4) and reclassified for Sapota-based and other agroforestry systems. Total 195 GPS points were collected for *A. zapota* trees from the farmers' fields in Vanthali and Una blocks of Junagarh district. Some of these points were used for making MOI (material of interest) which generated signatures for Sapota species, and remaining points were used for finding classification accuracy. Area under Sapota-based agroforestry comes out to be 9966.76 ha (1.13%) of the total area under agroforestry (Fig. 4.5). The accuracy of this classification

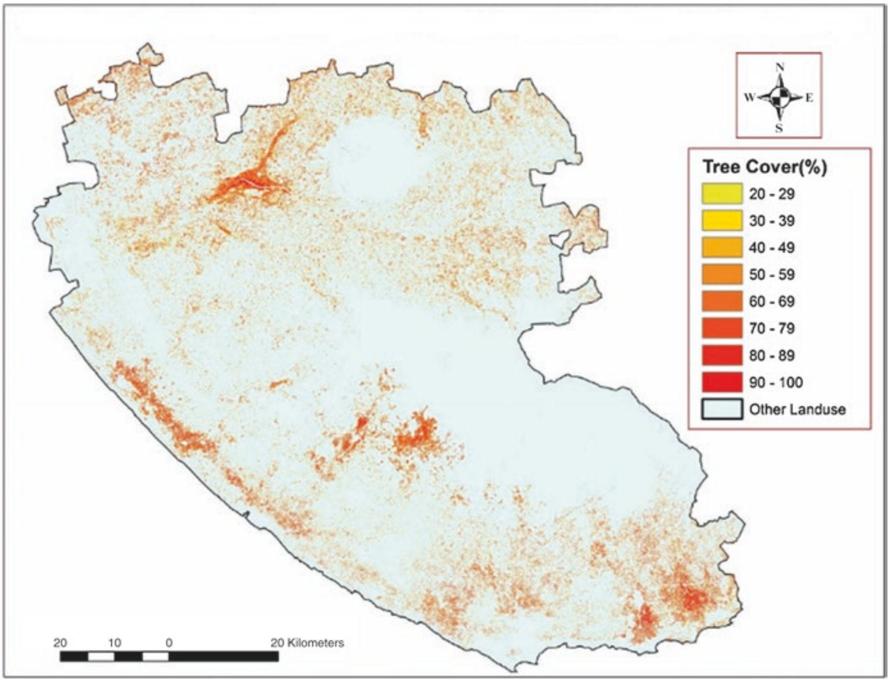

Fig. 4.4 Agroforestry area in Junagarh district obtained by subpixel classifier

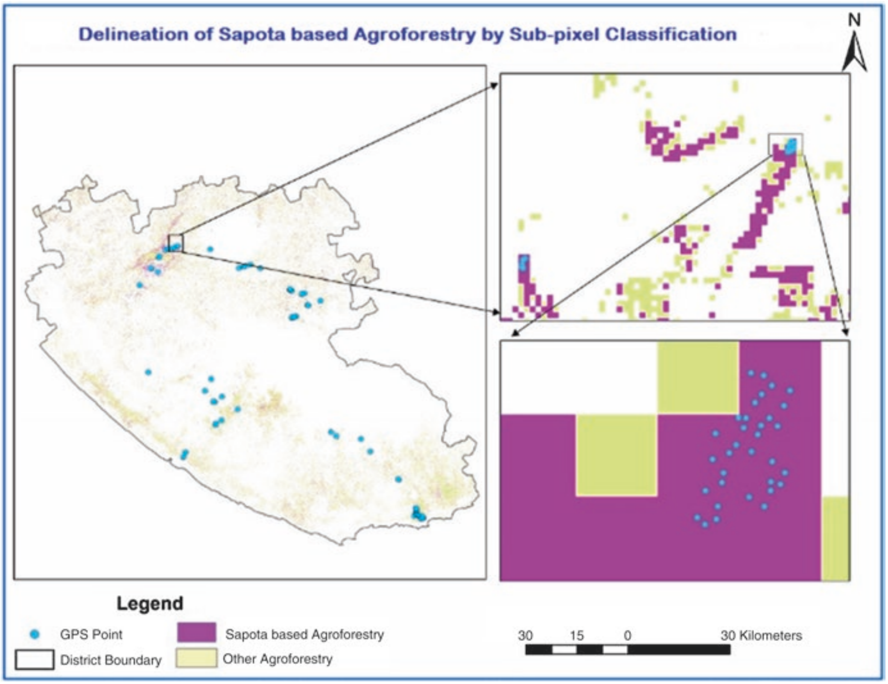

Fig. 4.5 *Achras zapota*-based agroforestry in Junagarh delineated by subpixel classifier

comes out to be 87.2% for Sapota species. Remaining 11.25% area was under other agroforestry systems like *Mangifera indica*-, *Emblica officinalis*- and *Ziziphus mauritiana*-based agri-horticulture systems (Rizvi et al. 2016b).

*4.2 Identification of Bamboo and Arjun (*Terminalia arjuna*) Species in North Dinajpur*

Rizvi and Airon (2012) attempted to distinguish tree species like bamboo and Arjun found in North Dinajpur district of W. Bengal using Resourcesat-1 LISS-IV data. For the identification of species, the spectral values were determined on remote sensing image with the help of GPS points collected from the fields. Distinct spectral values were found in three bands for two species. With the help of these spectral values, the spectral signatures were created, and image was classified by method of maximum likelihood. Of the total agroforestry area in the district, bamboo and Arjun species were found in 2.4 and 2.7%; mixed species like *Eucalyptus*, mango, etc. accounted for 30.7% area. *Bambusa* spp. (red colour) and *Terminalia arjuna* (magenta colour) species identified in North Dinajpur district are depicted in Fig. 4.6.

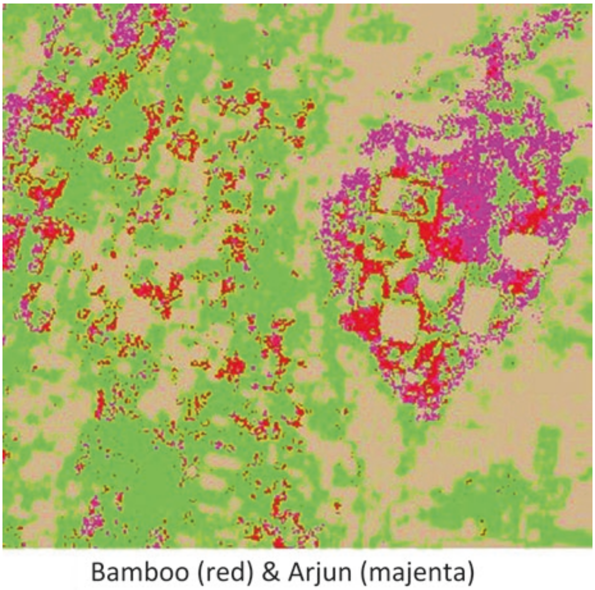

Fig. 4.6 *Bambusa* sp. and *Terminalia arjuna* identified through LISS-IV data

For identification of tree species, high-resolution/hyperspectral remote sensing data will be useful. Remote sensing data of spatial resolution better than 5 m can be effectively used for this purpose.

5 Assessment of Carbon Sequestration in Agroforestry

Several studies were conducted to assess the biomass and carbon in forests using geospatial technologies (Luther et al. 2006; Meyong et al. 2006). However, few studies have been found where geospatial technologies were applied for estimation of carbon stock and carbon sequestration under agroforestry. Carbon sequestration potential of agroforestry systems in four districts of Indo-Gangetic plains, namely, Sultanpur (UP), Ludhiana (Punjab), Vaishali (Bihar) and North Dinajpur (W. Bengal), has been assessed by Newaj et al. (2012). They found total carbon sequestration potential of 0.44 Mg C in each district. Singh and Chand (2012) estimated aboveground TOF phytomass and the carbon content of TOF using trees outside forest inventory data and high-resolution LISS-IV satellite data. The aboveground TOF phytomass varied from 1.26 Mg ha^{-1} in the scattered trees in the rural/urban area to 91.5 Mg ha^{-1} in the dense linear TOF along canal. Upgupta et al. (2015) demonstrated the potential of Cartosat-1-derived digital surface model and QuickBird texture image for the estimation of stand height, stem diameter, tree count and phytomass of important timber species. Rizvi et al. (2016b) estimated carbon stock under agroforestry in Anand, Dahod, Junagarh and Patan districts of Gujarat by adopting remote sensing and modelling techniques. Total carbon stock in all four districts for baseline and simulated period of 30 years was estimated to be 2.907 and 3.251 Mg, respectively. Therefore, for assessment of carbon stock and C-sequestration in agroforestry systems, two-way approach may be adopted. Firstly, area under agroforestry in a district is estimated through remote sensing using the same methodology discussed above. Secondly, carbon sequestration by agroforestry systems per hectare (biomass + soil carbon) is estimated through a carbon accounting CO_2FIX model. Finally, carbon sequestration by agroforestry systems in a particular district is obtained by multiplying the area under agroforestry with carbon sequestration per ha.

6 Development of Spectra Library and Decision Support Tools

For applications of geospatial technologies in agroforestry research like biomass/carbon estimation and identification of tree species on farmlands, we need to have pure spectral signatures. For this purpose, high-resolution/hyperspectral remote sensing can be more useful than medium-resolution data. Hyperspectral images provide ample spectral information to identify and distinguish spectrally unique materials. The library of such spectral signatures for agroforestry tree species over different seasons or phenological stages would help in identification of tree species and then estimation of aboveground biomass/carbon. Digital library of spectral signatures for major agroforestry tree species would also help in correct assessment of area under agroforestry in different agroclimatic regions.

For effective agroforestry planning, landowners and extension agents require information on potential tree and shrub components as well as geographic information for specific sites. A major challenge in developing agroforestry planning decision support tools (DST), however, is its complex nature requiring the need to bring together a variety of information (biophysical, economic and social factors) and evaluate this information at site-specific and landscape scales. Computer-based DST help to integrate information to facilitate the decision-making process that directs development, acceptance, adoption and management aspects in agroforestry. Computer-based DST include databases, geographical information systems, models, knowledge-based or expert systems and 'hybrid' decision support systems (Ellis et al. 2004). The Southeastern Agroforestry Decision Support System (SEADSS) developed by the Center for Subtropical Agroforestry (CSTAF) at the University of Florida brings on-line GIS capabilities directly to the extension agents and landowners. SEADSS offers on-line access to country-level spatial information, such as topography, hydrology, soils and land use, which are essential in evaluating potential agroforestry sites and suitable species (Ellis et al. 2005).

7 Conclusion

The application of GIS and RS technology in agroforestry is so far very limited in India, although these technologies have great potential in agroforestry research and may be used for estimating system production (biomass/yield), assessment of carbon sequestration, identification of areas suitable for agroforestry intervention, etc. However, for these applications, library of spectral signatures and spatial decision support system are pre-requisite. With the advent of hyperspectral remote sensing satellites, not only identification of tree species can be done, but tree canopies leaf area index can also be assessed. Besides this, tree counts, their heights and canopy structure can also be easily measured with the help of synthetic aperture radar (SAR) microwave remote sensing data. Therefore, there is a need to develop spatial decision support system (SDSS) for agroforestry development in India, which would help the planners and researchers in identifying suitable agroforestry systems for various agroclimatic regions.

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Chapter 5
Monitoring and Assessment of Trees Outside Forests (TOF)

P. Beckschäfer, S. Schnell, and C. Kleinn

Abstract In the context of the international conventions on climate change (United Nations Framework Convention on Climate Change, UN-FCCC) and biological diversity (United Nations Convention on Biological Diversity, UN-CBD), the demand for up-to-date information on tree resources within and outside forests is higher than ever before, urging for approaches to reliably monitor tree resources across large areas. While for the assessment of tree resources within forests a variety of sophisticated forest inventory methods has been developed and tested, fewer efforts have been undertaken that focus on the assessment of trees outside forests (TOF). While the variables of interest are essentially the same, main differences in the assessment of trees within and outside forests arise from the distinctive characteristics of TOF, including uneven spatial distribution, specific geometric arrangements, specific functions, and the presence of other land uses. In this chapter, we give an overview of inventory approaches suitable for the science-based assessment of TOF, with a focus on agricultural lands, and highlight how inventory designs developed for forest inventories may be adapted to the assessment of trees on non-forest lands. The chapter covers considerations about operational definitions of TOF, describes implications resulting from modeling tree attributes using allometric models, and reviews the application of different response (plot) designs used in ground-based or remote sensing-based TOF assessments. Further, current approaches to monitor TOF resources with active and passive remote sensing sensors, such as LiDAR, RADAR, SPOT, RapidEye, Landsat, MODIS, etc., are presented, and besides, it is outlined how field inventory data and remote sensing data can potentially be integrated to increase the precision of parameter estimates.

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1 Introduction

Forest inventories have a long history and are generally acknowledged to be basic components of forest management and forest policy decision processes, as well as input to research (Tomppo et al. 2010). Intensive research and broad implementation experiences have led to the availability of a versatile forest inventory toolbox so that sampling design, plot design, and modeling components as well as the integration of different data sources can be tailored to the specific goals and circumstances for particular inventory projects (Tomppo et al. 2011), be they for smaller areas (forest management inventories) or for larger areas (national forest inventories).

Currently, in the context of the international conventions on climate change (UN-FCCC) and on biological diversity (UN-CBD), the demand for up-to-date information on the forest resource and the forest ecosystem is higher than ever before. This information demand is not specifically restricted to "trees as part of forests" but in a wider sense also to "trees in general". When it comes to quantifying carbon sinks and sources as well as ecological functions, trees that are not part of the forest are also contributing, even though in a different manner. The reason why trees outside forests (TOF) are attracting more and more attention is simple: the increasing human population and the increasing wealth and resource consumption put immense pressure on the remaining forest areas, so that for the protection and enhancement of tree cover, also non-forest lands will be needed as a complement for the protection of forest areas (Plieninger et al. 2015).

Forest landscape restoration is an initiative into that direction that gains momentum currently. The New York Declaration on Forests (UN 2014) makes explicitly reference not only to restoration of degraded forests but in more general terms to forested landscapes: "Restore 150 million hectares of degraded landscapes and forest lands by 2020 and significantly increase the rate of global restoration thereafter, which would restore at least an additional 200 million hectares by 2030." These ambitious goals are immediately reflected in the Bonn challenge, "a global effort to restore 150 million hectares of the world's deforested and degraded lands by 2020 and 350 million hectares by 2030" (IUCN 2011). More specifically, for example, AFR100 – the African Forest Landscape Restoration Initiative – has the goal "to restore 100 million hectares of deforested and degraded landscapes across Africa by 2030" (WRI 2015). One of the showcases in this initiative is the farmer-driven significant increase of tree cover on agricultural lands in Niger that lead to an equally significant improvement of livelihoods.

All these activities do also refer to TOF, including trees on agricultural lands and in agroforestry systems. A binding mechanism for implementation, though, has not yet been established beyond political commitments of partner countries and institutions, and neither have financing mechanisms been negotiated. However, given the definition of very ambitious goals in terms of area and timing, it is likely that such financing mechanisms will arise; then, at the latest, there will be an urgent demand for approaches to reliably monitor the performance and/or results of forest landscape restoration projects over larger areas, similar to what is currently been implemented through MRV (measurement, reporting, verification) in REDD+ finance.

In fact, there have been various approaches to integrate the assessment of TOF into regular forest inventories over several decades, e.g., the inventory of hedge rows in France (Chevrou 1973) and the Countryside Survey in England (CEH 2007). In India, the relevance of reliable information on the important tree resource TOF in the country has been intensively discussed at the latest since the 1980s, mainly in the context of social forestry and the role of TOF for rural livelihoods. The Forest Survey of India has then integrated the assessment of TOF into their regular program of national forest inventories since 1991 (Pandey 2008b), and in the forest inventory methodological approach of FAO's NFMA (National Forest Monitoring and Assessment) program, the assessment of TOF has been included since the pilot inventory was carried out in Costa Rica in 2000 (Kleinn et al. 2005). Also, no. 200 of *Unasylva*, FAO's forestry journal, was dedicated to TOF, containing a paper specifically on assessment issues (Kleinn 2000). A compilation of large-area assessments, including instructive figures for 11 countries, where FAO supported national assessments, is in Schnell et al. (2015a).

In this chapter, we give an overview of inventory approaches suitable for the science-based assessment of TOF, specifically on agricultural lands. Most inventory approaches applied and discussed in the literature have their origin in forest inventory. The adaptations of the inventory designs to trees on non-forest lands come from the distinctive characteristics of TOF, including uneven spatial distribution, specific geometric arrangements, and presence of other land uses. The variables of interest that are recorded are essentially the same as in forest inventories, except maybe for the fact that trees on non-forest lands do frequently have specifically intended functions.

Our review is restricted to technical approaches of sampling, modeling, and remote sensing – and we do not deal with practical challenges of implementation which arise when, for example, in large-area assessments, tree measurements need to be made on many different land use types and land ownerships.

2 Definitions

Unambiguous definitions of all variables to be assessed and analyzed, including definitions of their observation (measurements for metric variables and categories for categorical and nominal variables), are among the most relevant foundations of all monitoring that aims at producing reliable science-based and meaningful statistics on tree and forest resources. In addition, unambiguous definitions of all variables do significantly contribute to transparency which is an important and frequently demanded property of monitoring approaches implemented in the context of international conventions. From a science point of view, statistics are of limited value if they cannot be properly (=unambiguously) interpreted due to unclear protocols – even though such fuzzy types of results may be welcomed by some policy decision-makers. Comprehensive, detailed, and clear monitoring protocols are of particular relevance in large-area monitoring projects that involve numerous people and aim at providing information for a variety of stakeholders with different interests, backgrounds, and understandings of terms. Thus, also the concept of *trees outside forests* needs to be clearly defined in the context of large-area monitoring of tree resources.

Trees outside forests refer to all trees that grow on non-forest land categories so that the definition of TOF strongly relies on a workable definition of forest (Schnell et al. 2015b).

However, while *forest* means implicitly *forest land* and is an area category from the outset, TOF is per definition focusing on the trees, not the land. Consequently, when operationalizing it for inventory projects, TOF can hardly be treated as an area category of its own. TOF are rather present on all non-forest lands, in varying densities and configurations, of course. In that sense, we advocate the view to consider the presence and density of trees (TOF) as a characteristic of non-forest land use classes, just as other features like the length of creeks or the presence of infrastructure. Such a view is easy to understand and can be operationally applied in tree monitoring.

Defining *forest* – and therefore also non-forest as the inverse category – appears to be straightforward at first sight but is in fact quite complex as the perceptions of forests differ from person to person resulting in multiple understandings of what criteria characterize a forest. As a consequence, no universal forest definition has been agreed upon so far (Chazdon et al. 2016), and instead nearly 1600 different forest definitions are or have been used around the world (Lund 2014). In the context of climate change mitigation, it is currently even debated whether a distinction of forest and TOF is appropriate at all as carbon emissions can originate from both categories making an assessment of trees across the landscape independent of forest definitions necessary (Chazdon et al. 2016; van Noordwijk and Minang 2009).

The framework of land use definitions provided by the Food and Agriculture Organization (FAO) of the United Nations is frequently referred to as global reference; these definitions are results of intensive international discussion processes. We revisited FAO publications concerning definitions used in the Global Forest Resources Assessment (FRA) since 2000 and found that only for the years 2000 and 2005 a TOF definition was explicitly formulated (FAO 2001, 2006), defining TOF as all trees found outside *forests* and *other wooded lands*. Inverting the respective definitions of *forest* and *other wooded land*, TOF are trees that grow on lands with a combined cover of shrubs and trees of less than 10% or a tree cover of less than 5%. Trees on land with a predominantly agricultural or urban land use or groups of trees covering less than 0.5 ha are always TOF independent of the crown cover (Schnell et al. 2015b). Hence, following FAO's definition, trees growing in agroforestry systems or on other non-forest land uses are classified as TOF, regardless of tree density and patch size. With FRA 2010, the nomenclature used by FAO slightly changed as the category *other land with tree cover* was added to the FRA manual as a subcategory of *other land*, and no explicit TOF definition was formulated anymore. *Other land with tree cover* was defined as land not classified as *forest* or *other wooded land*, spanning more than 0.5 ha with a canopy cover of more than 10% of trees able to reach a height of 5 m at maturity (FAO 2010, 2012a). According to this definition, agroforestry systems that meet the above mentioned thresholds are since then classified as *other land with tree cover* and scattered trees and smaller tree groups fused into the category *other land* which besides encompasses all permanently unstocked lands. Anyhow, even though TOF appears not to be specifically defined in the current FRA manual, FAO has a strong interest in gathering knowledge on TOF and encourages countries to carry out timely and high-quality assessments of TOF at a national level (FAO 2010) and continues to work on a better integration of TOF into the FRA reporting process (e.g., de Foresta et al. 2013).

From a monitoring perspective, a definition should of course be meaningful, but the most important criterion is that the definition is clear and unambiguous and both consistently and universally applicable. All operators – whether in the field or during remote sensing image analyses – must produce as consistent as possible observations. Here, a particular and actually little researched challenge is the compatibility between field observations and remote sensing classifications. Among the few studies that look, for example, at the implementation of the FAO forest definition in remote sensing image processing are Magdon et al. (2014) and Eysn et al. (2012).

In this section, for reviewing assessment techniques for TOF, we are not looking at TOF as an own land category, but do rather apply the common forest inventory approach: characterizing the land categories through their tree covers. That means that the land is the reference and its area defines the sampling frame: in the case of forests, it is *forest land*, and in the case of TOF, it is the non-forest lands. In a large-area inventory project, these two classes may be considered subpopulations or strata and need to be distinguished (which is done in any case in forest inventories that refer to forest only, leaving the remaining land as non-forest). The differences in the assessment techniques between a forest inventory and a TOF inventory are then coming from the different characteristics of the trees (density, diameter distribution, taper, functions, etc.) on these two classes of land: forest and non-forest.

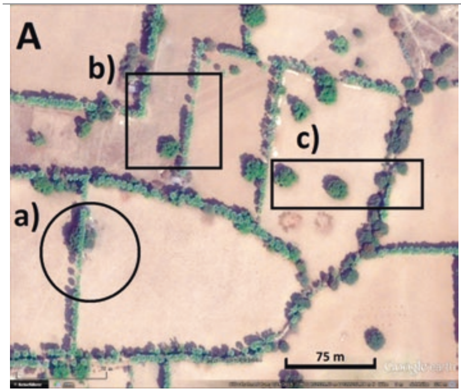
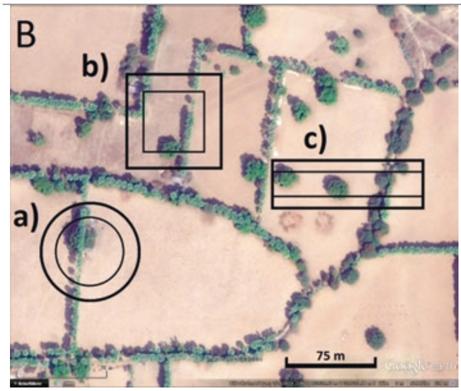
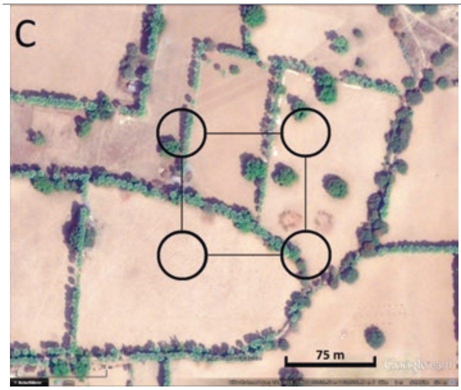
3 Response Design

As already indicated in the previous section, the sampling frame is the area that is going to be monitored, and the population of interest comprises all trees that grow within that area in varying density and spatial configuration. This distinction between sampling frame and population of interest is a common necessity in forest inventories as enumerated lists of population elements (trees) are typically not available. Sampling has thus an indirect nature because population elements are accessed through the sampling frame and not directly. Within areal sampling frames, as commonly used in forest or tree inventories, locations for data collection are selected according to a probabilistic sampling design (simple random sampling, systematic sampling, etc.), and typically, a clear rule is defined, how to identify sample trees around these sample points that are measured for many variables. This rule and the list of variables to be observed are referred to as "response design," also known as "plot design" or in more general terms "observation design."

A very common response design in forest inventories is the application of fixed-area sample plots (Tomppo et al. 2010), where all trees within the plot area are selected for measurements (Table 5.1A). Number, shape, and size of the plots are chosen based on statistical and practical considerations (including experiences and traditions) and form a typical trade-off between time consumption and sample precision (Tomppo et al. 2011). Plot sizes that have been used for assessing TOF range from 150 m^2 (temporary plots in the Swedish NFI, Fridman et al. 2014) to 5000 m^2 (NFMA inventories, FAO 2012b). In national-level forest monitoring, it is common to split plots spatially to form clusters of plots (Table 5.1C) in order to optimize data collection for travel time (Tomppo et al. 2014). Further, often multiple, nested plots of different size are established at the same sample location to avoid redundancy from the inclusion of too many small trees (small areas for small trees – large areas for large trees) (Table 5.1B). Compared to inventories within forest stands, it is more challenging to plan the fieldwork in TOF inventories because the usually higher variation of tree densities makes it difficult to anticipate the expected number of trees per plot and, thus, the time needed to measure them. To solve this problem, two-phase sampling designs can be applied, where in a larger first-phase sample, only local tree density is assessed, and in a smaller second-phase sample, plot size is adapted to the local conditions (e.g., Lam et al. 2011). Summarizing, fixed-area plots can be considered a general-purpose response design that is not optimized towards a specific target variable and can be used to obtain estimates with generally acceptable precision in multipurpose inventories, where many variables are collected for estimating a variety of population characteristics. In addition, fixed-area plots have certain advantages when field data are to be combined with remote-sensing products. Anyhow, if certain target variables (e.g., biomass) are of greater importance than others, it could be advisable to use a response design that is optimized towards the estimation of that variable and, hence, results in a comparably smaller sampling error.

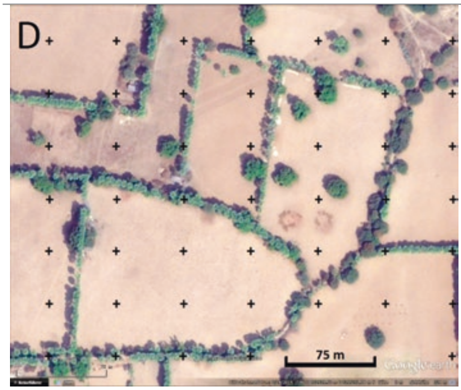
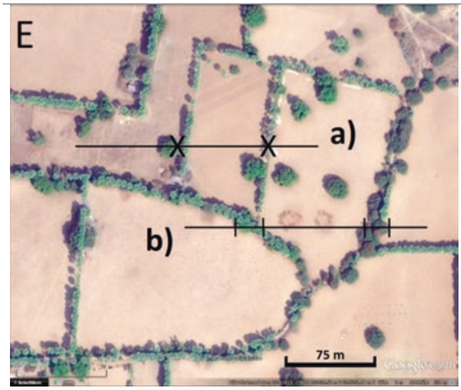
In addition to two-dimensional sample plots, one-dimensional sample lines (Table 5.1E) and dimensionless sample points (Table 5.1D) can be used as response design as well (de Vries 1986; Fehrmann et al. 2014). The latter two are usually not used for selecting trees but for directly measuring some variables of interest. In *line intersect sampling*, sample lines are used for assessments of linear features, such as hedgerows or windbreaks (Hansen 1985), where a mere count of intersections between features and sample lines is enough to provide estimates of total length in the study area (Gregoire and Valentine 2008, Chap. 9). For other variables, the length of the selected element needs to be measured. Using *line intercept sampling*, sample lines are used to estimate area proportions, such as crown cover (Fehrmann

Table 5.1 Response/plot design examples. Using high-resolution satellite data (Google, Digital Globe) of an agricultural area in Myanmar and a subset of the city of Hyderabad, India, as background images, various plot designs are presented and their characteristics described. For all plot types, slope corrections need to be considered. The plots depicted in panels A–C have an area of 5000 m^2 each; the smaller, nested subplots (panel B) have an area of 2500 m^2; the subplots of the cluster plot (panel C) have an area of 1250 m^2 each. The central coordinates of the images in panels A–E and panel F are WGS84, UTM 46Q732683 E, 2355365 N and 44Q 232920 E, 1924600 N

	Fixed-area plots
	Easy to implement and understand
	All trees with their stem axis within the plot area are selected as sample trees
	Plot size and shape are chosen along practical and statistical considerations
	Fixed-area plots with nested subplots
	Easy to implement and to understand
	Plot size and shape are chosen along practical and statistical considerations. Subplots are used to avoid having too many sample trees, for example, larger trees (diameter at breast height – dbh – of more than 7 cm) are selected on the entire plot area, and smaller trees (dbh ≤ 7 cm) are selected on the smaller subplot. Subplot sizes can be optimized when the distribution of the respective tree characteristic is known
	Cluster plot
	A cluster plot consists of various subplots but counts statistically as one single "funny-shaped" plot. Number, spatial arrangement, size, and shape of subplots are defined along practical and statistical considerations. Combinations of different plot types are also possible, e.g., *circular subplots for living vegetation and sample lines for dead wood*
	Compared to a compact fixed-area plot of the same size, the cluster plot captures a larger variability as it reduces redundancies due to spatial autocorrelation effects

(continued)

Table 5.1 (continued)

	Grid of dimensionless points *Only categorical variables can be observed,* e.g., *land cover (tree or not-a-tree). Area and area proportions for target categories* (e.g., *crown cover) can be estimated by observing the "condition class" in which the points fall. Here, 11 out of 49 points are located on tree crowns, so that the estimate of tree cover results as* $11/49 \times 100 = 22.4\%$ *with a standard error of* $((0.224(1 - 0.224))/(49 - 1))^{0.5} \times 100 = 6\%$
	Line plots (a) Line intersect sampling *Counting how many times the line plot intersects with linear landscape elements,* e.g., *hedgerows, allows for estimating the total length of the respective features* (b) Line intercept sampling *Observing which proportion of the line plot is located in a certain land cover class allows for estimating the percent cover of the respective class*
	City blocks *Large plots of variable area and shape defined along population characteristics,* e.g., *number of households. Blocks are selected from a list, and observations are made on all trees whose center points are located within them. This reduces traveling time among plots but results in irregularly shaped plots of variable area*

et al. 2014). The estimation of area proportions is also the main application of sample points. Both sample lines and points have in common that they are mainly applied on aerial photos or high-resolution optical satellite data, e.g., in earlier phases of multiphase sampling strategies.

Bitterlich or relascope plots (Gregoire and Valentine 2008, Chap. 8), which facilitate a selection of trees proportional to their basal area through an angle gauge, have not been used in TOF surveys yet. The advantage of this response design is that for variables that are related to basal area (e.g., volume, biomass, carbon), the application of Bitterlich plots results in lower sampling errors. Drawbacks are that for the estimation of other stand characteristics, such as tree density, lower precision is to be expected. In addition, local estimates cannot be related to a specific section of land, which makes a linking to remote sensing data rather difficult. In cases where low tree densities or irregular spatial patterns are expected, issues related to the geometrical properties of tree arrangements arise that rather speak against the application of Bitterlich plots. For example, when tree density is low, opening angles need to be large to include an appropriate number of trees. The rather long distances that might then occur between sample location and trees would be difficult to handle.

A rather uncommon response design has been implemented by Corona et al. (2011) within a two-stage sampling strategy for monitoring TOF that occur in small patches. The so-called sector plots (Iles and Smith 2006) were originally proposed for sampling retention areas after clear cuts. The design is such that a sample point is randomly located within smaller wooden patches. From the sample point, a sector with fixed angle is installed, and all trees within this sector are selected for the sample. The advantage of the method is that no correction for edge-effect bias known from traditional sample plots (Gregoire and Valentine 2008, chap. 7.5) needs to be applied.

Adaptive plot designs as introduced by Thomson (2012, pt. 6) have appealing characteristics when it comes to the assessment of TOF. The strongly varying densities and arrangements of TOF lend themselves, in principle, to adaptive definitions of plot sizes. To avoid many empty plots and to collect as much information as possible once at the selected sample points, one may wish, for example, to adjust the plot size to the situation encountered at the specific sample point. While this approach sounds straightforward and attractive from a practical implementation point of view, one should employ it only when suitable (unbiased) estimators are available or can be developed to allow reliable estimation. These estimators may turn out extremely complex, requiring various additional measurements in the field (e.g., Yang et al. 2016) so that these plot designs are hardly ever used in practice.

Fixed-count plots (also called *k*-tree plots) are a plot design where from the sample points the *k* nearest trees are included as sample trees. This plot design shares some implementation characteristics to adaptive plots in that the “virtual plot area” in *k*-tree plots adapts to the local density of trees, when one assumes that the radius of such a virtual plot area is defined by the distance to the *k*th tree. This plot design is very often used in ecological surveys but no longer in forest monitoring, the reason for the latter being that there is so far no design-unbiased estimator that can easily be applied in practice (Kleinn and Vilčko 2006a, b) and that the model-assisted estimators are complex.

At the end, as in forest monitoring, it is likely that integrated fixed-area plots are the plot design to be preferred, because estimation is straightforward and there is a high degree of flexibility to integrate additional plot design elements (Kleinn and Vilčko 2006a).

In addition to area sampling frames, list sampling frames were used in some cases for TOF inventories. In the Indian NFI, for example, lists of city blocks are used for urban tree assessments (Table 5.1F). City blocks are sampled from the list and all trees within a block are measured (Tewari et al. 2014). Similarly, Corona and Fattorini (2006) sampled from a list of tree rows that was enumerated from aerial imagery. Finally, when remote sensing data is an integral part of a monitoring strategy in the sense that either model-based inference or model-assisted estimation is applied (Ståhl et al. 2016), the sampling frame is inherently a list of remote sensing data pixels that cover the study area.

4 Allometric Models

Among the key objectives of tree inventories is the generation of information about the growing stock that is available in an area of interest. Depending on the specific goals of an inventory, growing stock can be described in terms of basal area, timber volume, biomass, or carbon content of trees, but as volume, biomass, and carbon content can only be measured through time-consuming and impractical destructive measurements, allometric models are required that allow for their estimation based on easy-to-observe tree variables such as diameter at breast height, height, species, and to some extent wood-specific gravity.

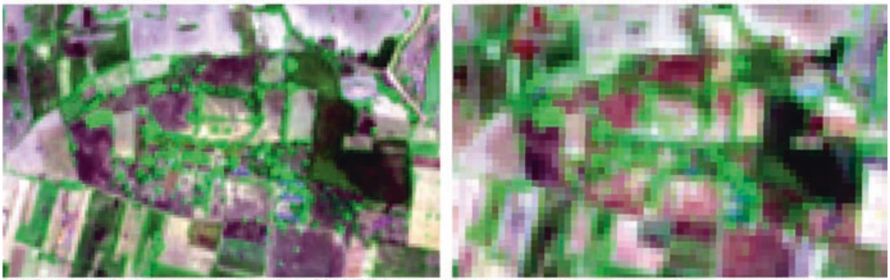
Allometric models are available in rich diversity for forest-grown trees (Henry et al. 2013). One can find species-specific models, limited to local conditions on the one end of the spectrum and, on the other end, species-generic models that are applicable for certain forest biomes at a global level (e.g., Chave et al. 2014). For TOF in urban and agricultural environments, the availability of allometric models is limited, although more and more studies have recently been undertaken to close the gap (e.g., Kalita et al. 2015; Kuyah et al. 2012a).

If applying allometric models in tree inventories, two effects that influence the results need to be considered: (1) biased estimates of confidence intervals if uncertainty due to model application is ignored and (2) biased point estimates if allometric models are used that do not match the relationships of the target population (e.g., forest models applied to TOF). Using allometric models in tree inventories introduces uncertainty through (1) residual variance around model predictions, (2) uncertainty in parameter prediction, and (3) variability in predictor variables from measurement errors (Chen et al. 2015). A general assumption often made in forest inventories is that this uncertainty can be ignored as it is negligible when compared to the error introduced by the sampling nature of the inventories. Studies by Breidenbach et al. (2014), McRoberts and Westfall (2014), and McRoberts et al. (2015) support this assumption when simple random sampling estimators of the population mean were applied. In contrast to these findings, Ståhl et al. (2014) reported an underestimation of the uncertainty of 10% also using simple random sampling estimators. Other studies as well reported non-negligible effects if model-related errors were ignored (Chen et al. 2016; McRoberts et al. 2016; McRoberts and Westfall 2015). The application of sampling and estimation strategies that yield lower sampling errors (stratification, spatially balanced designs, post-stratification, model-assisted estimation, etc.) leads to an increased relative contribution of allometric model estimator variance to the total error budget, but also the usage of either species-specific or non-species-specific models had an effect. Applying regression estimation and a non-species-specific allometric model, McRoberts et al. (2016) reported a bias in variance estimation of up to 368% when the variance of the allometric model estimator was ignored. For the case of TOF inventories, we assume that effects will be in the same range as reported for forest inventories if not larger because of the increased uncertainty in model parameter prediction due to the typically smaller datasets that are available for developing allometric models and because of the higher chance that models are being applied that had not specifically been developed for non-forest trees. Further, allometric relationships in the TOF realm are likely to be not as close as in forest stands because of the higher variability of growth conditions (from isolated trees to forestlike stand conditions) and management practices (e.g., pruning activities). Here, additional proxy variables, such as crown height or area, that better describe the variability in crown mass might be included in the modeling (Kuyah et al. 2012b), as is increasingly discussed for forest trees as well to improve biomass prediction for, in particular, large trees (Goodman et al. 2014; Ploton et al. 2016).

If allometric models suitable for the target population of TOF are missing, the common practice is the application of species-generic forest models (McHale et al. 2009; Nair 2012). The direction and amount of the bias originating from this practice have been investigated by several studies (Kuyah et al. 2012a, b; McHale et al. 2009; Yoon et al. 2013); however, no general rule of thumb can be inferred as results to whether over- or underestimation might be expected are indifferent. Similar observations were made by Yuen et al. (2016), who reviewed allometric equations for major land uses in Southeast Asia. A general advice from this study is to compare several potential equations and report the range of estimates (Yuen et al. 2016) as results from different model equations can vary tremendously in particular for larger trees. It is further important to assure that the diameter range of existing models fits to the range that is expected to be found in the study area. Finally, existing models should be validated by destructively sampling trees (Yuen et al. 2016), e.g., using the methodological framework introduced by Pérez-Cruzado et al. (2015). As an alternative to destructive sampling, non-destructive volume measurements from terrestrial laser scanning (Calders et al. 2015; Lefsky and McHale 2008) or optical instruments might be applied.

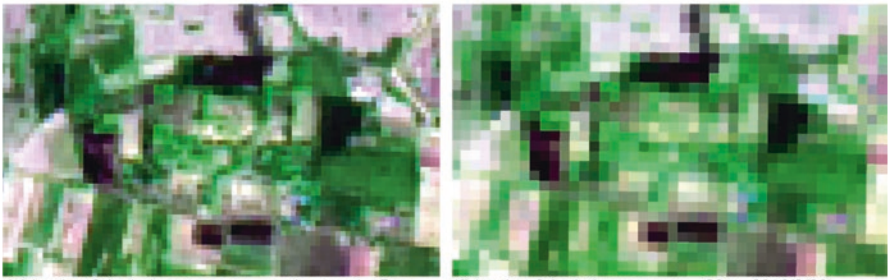
(a) Digital Globe (true color composite, <1 m, 2016/4/24)

(b) Sentinel-2 (red-nir-green comp., 10 m, 2016/1/11)



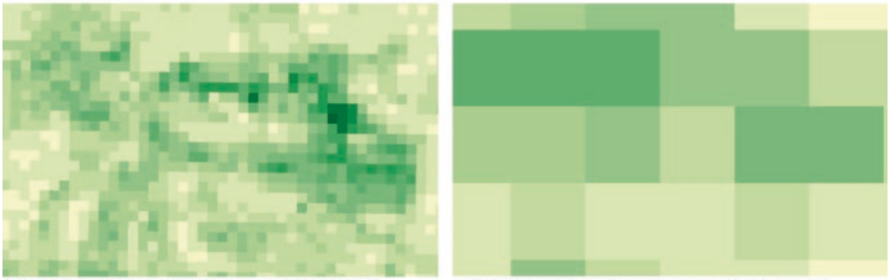
(c) Sentinel-2 (red-nir-green comp., 10 m, 2016/5/9)

(d) Sentinel-2 (swir1-nir-red edge comp., 20 m, 2016/5/9)



(e) Landsat 8 (red-nir-green comp., pansharpened, 15 m, 2016/3/20)

(f) Landsat 8 (red-nir-green comp., 30 m, 2016/3/20)



(g) Landsat vegetation continuous field (30 m, 2015)

(h) MODIS vegetation continuous field (250 m, 2010)

Fig. 5.1 How are TOF picked up by remote sensing products with different spectral and spatial resolutions? All panels show the same piece of land located approx. 25 km north of Bangalore, India (central coordinate: WGS84, UTM 43P 780200 E, 1466350 N), at about the same date and, if possible, using the same combination of spectral bands. The depicted area contains a diverse mixture of agricultural fields, single trees, tree groups, tree plantations, and built-up structures. Panel (**a**) shows a high-resolution image (Google, Digital Globe) downloaded via Google Earth in which most TOF features can easily be distinguished from other land cover by the human eye. In

Another source of uncertainty in the application of allometric models originates from the usage of wood-specific gravity (WSG) as a predictor variable in species-generic models, where WSG is used as a proxy for species information. Errors might arise from assigning wrong WSG values, usually taken from public databases, to the inventoried trees due to erroneous or missing species identification in the field. Additionally, WSG values of individuals of the same species are strongly influenced by environmental factors and can cause substantial variation in final biomass estimates if values taken from databases do not match local conditions (Yuen et al. 2016). Zhou et al. (2007), for example, observed larger WSG values for the trunk wood of shelterbelt trees than for forest trees of the same species. As a solution, WSG might be assessed for each individual tree either by collecting small specimen or by using portable wood densitometers such as the Pilodyn device (e.g., Mäkipää and Linkosalo 2011).

5 Remote Sensing

Trying to fill the information gap concerning the amount and distribution of TOF on agricultural lands, several remote sensing-based techniques have been employed. This can be a challenging task, as TOF per definition can be of small extent and of sparse and variable spatial arrangement, and thus, not all types of TOF are easily detectable from space. Besides the size and variability of the TOF class itself, also the background against which TOF have to be detected is often very heterogeneous, as the matrix of agricultural fields usually consists of a mosaic arrangement of various crops with variable spectral characteristics and crop cycle dynamics. These factors make the assessment of TOF with remote sensing techniques more complex than, e.g., the assessment of land cover classes of large areal extent, such as forests. Exemplarily, Fig. 5.1 illustrates how TOF in a landscape dominated by agricultural fields are picked up by remote sensing sensors/products with varying spatial and spectral resolution. Further, Fig. 5.1b, c demonstrates how the spectral characteristics

Fig. 5.1 (continued) the following panels (**b**–**f**), a distinction of TOF by eye becomes more difficult due to coarser resolution imagery provided by the Sentinel-2 and Landsat 8 satellites. Panels (**b**) and (**c**) show images taken with the same sensor (Sentinel-2) but acquired ca. 5 months apart to illustrate how the contrast between trees and agricultural units changes in dependence of the agricultural period. While the trees prominently stand out against the mainly bare soils of the unworked fields in panel (**c**), they appear less distinct in panel (**b**) in which a larger share of fields is vegetated with crops. Panels (**g**) and (**h**) illustrate how the Landsat and MODIS vegetation continuous fields products depict the area. These remote sensing products contain for each pixel a percent value of the area covered with trees higher than 5 m. Both panels (**g**) and (**h**) use a common color scale ranging from light green (1% tree cover) to dark green (12% tree cover) (**a**) Digital Globe (true color composite, <1 m, 2016/4/24) (**b**) Sentinel-2 (red-nir-green comp., 10 m, 2016/1/11) (**c**) Sentinel-2 (red-nir-green comp., 10 m, 2016/5/9) (**d**) Sentinel-2 (swir1-nir-red edge comp., 20 m, 2016/5/9) (**e**) Landsat 8 (red-nir-green comp., pansharpened, 15 m, 2016/3/20) (**f**) Landsat 8 (red-nir-green comp., 30 m, 2016/3/20) (**g**) Landsat vegetation continuous fields (30 m, 2015) (**h**) MODIS vegetation continuous fields (250 m, 2010) of the agricultural matrix change with time, adding another level of complexity to the remote sensing-based assessment of trees on agricultural lands. Even though there are specific challenges, many of the available satellite remote sensing data sources have been tested for their applicability to assess TOF from space.

Active remote sensing techniques, such as light detection and ranging (LiDAR) and radio detection and ranging (RADAR), could in theory be of great use for the assessment of TOF features as they have the potential to describe both the horizontal and the vertical distributions of the vegetation in the landscape. An assessment of TOF could, thus, be based on surface height since trees are comparably higher and of different structure than the crops planted in the agricultural matrix. Anyhow, to our best knowledge, there is only one study using RADAR data (Devaney et al. 2015) and only few studies that applied airborne LiDAR scanner (ALS) data (Eysn et al. 2012; Johnson et al. 2015; Straub et al. 2008) to monitor TOF on agricultural lands. Full-waveform ALS data were used by Straub et al. (2008) who developed a two-step approach to (1) distinguish vegetated from non-vegetated areas based on the ALS-derived height profile and (2) to subdivide the vegetated areas into the classes forest and TOF based on their geometric properties (area, height, crown cover, and width). The resulting map had an overall accuracy of 97%, but tree groups and single trees were mapped with lower accuracies of 78% and 68%, respectively. Eysn et al. (2012) used ALS data to identify the positions of individual tree tops and determined the crown cover in polygons surrounding each tree top delineated by a Delaunay triangulation. Polygons reaching a certain crown cover percentage were merged and subsequently checked for area and width. The resulting forest maps had a high accuracy, but non-forest land uses (e.g., fruit orchards) posed a challenge. Devaney et al. (2015) assessed the potential of RADAR data for the estimation of forest cover in a fragmented landscape with sparse tree cover in Ireland. The study used L-band Synthetic Aperture Radar (SAR) data from the ALOS satellite and focused on mapping groups of trees of at least 0.1 ha size. They concluded that (1) spaceborne RADAR could aid inventories in regions with low levels of forest cover and (2) that RADAR-derived maps of tree cover may also be applicable to the assessment of TOF. They further pointed out that the free and open access policies for, e.g., Sentinel-1A/B RADAR data constitute a basis for incorporating RADAR-derived forest cover estimates into national reporting mechanisms. As an alternative to active remote sensing sensors, three dimensional data can also be derived from photogrammetric matching of aerial images (Bohlin et al. 2012), but this approach has not yet been tested in a TOF-specific context.

To monitor TOF on agricultural fields, high-resolution optical remote sensing data, such as aerial images with submeter pixel size or satellite images with a spatial resolution of less than 2.5 m, e.g., IKONOS and QuickBird imagery, are either applied as the basis for sample-based assessments (e.g., Fehrmann et al. 2014) or as an input to generate detailed vegetation maps (e.g., Tansey et al. 2009). In sampling studies, image subsets, so-called photo plots, are selected as sampling units which are visually interpreted by an operator to completely delineate TOF and other land cover classes (Fehrmann et al. 2014; Ståhl et al. 2011a; Walton et al. 2008). Instead of fully delineating photo plots, they could also be sampled again by placing a set of points or lines over the plot on which the variables of interest are observed (Fensham and Fairfax 2002; Hansen 1985; Holmgren et al. 1994; Walton et al. 2008). From the observations made on the photo plots, target variables, e.g., tree cover or total length of linear TOF features, can then be estimated. Another approach to integrate high-resolution remote sensing data into sampling studies is to enumerate the TOF population in the imagery and then select a sample from this population for field visits (Corona and Fattorini 2006; David and Rhyner 1999; Wiseman et al. 2009).

If detailed vegetation maps are to be generated based on optical high-resolution imagery, researchers frequently chose to apply object-based classification approaches which attempt to implement a “real-world interpretation” of the imagery by setting each pixel into the context with its neighboring pixels. To achieve this, a segmentation algorithm is applied to the image which groups spatially contiguous pixels of similar values into objects. In a second step, these objects or segments are then classified into the land cover classes of interest based on spectral, textural, and/or geometrical characteristics (Liknes et al. 2010). This approach has been applied to map tree cover (Liknes et al. 2010; Meneguzzo et al. 2013) and woodlots, hedgerows, crops, etc. (Tansey et al. 2009) in agricultural areas. An observed difficulty of the object-based approach was the definition of a set of configurations that avoids over and under segmentation (Taubenböck et al. 2010), and it was further doubted that the methods developed at one site would be stable across larger regions and can be transferred to other sites (Liknes et al. 2010). However, Schumacher and Nord-Larsen (2014) indicated that the approach can be used for TOF classification on large, regional scales, and Meneguzzo et al. (2013) found that even though the object-based approach tended to overestimate total tree cover, it produced a more realistic spatial pattern of TOF compared to an unsupervised pixel-based classification.

At medium spatial resolution (2.5 m–60 m pixel size), images from the Landsat and SPOT satellites are commonly used for TOF studies in agricultural lands. Contrary to high-resolution imagery, in which TOF elements are composed of several pixels, the 30 m resolution of the Landsat sensors, for example, provides so-called mixed pixels which frequently contain the spectral information of several land cover classes. TOF elements, being often smaller than a single pixel, are therefore difficult to detect with standard multispectral classification approaches in medium-resolution images (Foschi and Smith 1997). As a solution to this problem, artificial intelligence strategies such as neural networks and machine vision to detect sub-pixel objects (narrow hedgerows and single trees) were proposed by Foschi and Smith (1997). Thornton et al. (2007, 2006) used pixel swapping to map TOF elements that are smaller than single pixels. The pixel swapping approach provides information on the proportions of each individual land cover class contained within a single pixel. These pixels are then resampled to a higher spatial resolution, and each sub-pixel is assigned a single land cover class considering the values of the neighboring pixels and the original class proportions. Without considering mixed pixels specifically, Levin et al. (2009) used SPOT 5 images to detect large paddock trees (diameter at breast height of more than 20 cm) in southeast Australia. They performed an object and a spectral recognition method which both resulted in high classification accuracies of more than 90%. To map apple orchards in the western Himalaya region of India, Kumar et al. (2008) used images from the Indian IRS satellite (22.5 m pixel size). The peculiarity of their study site was that it consisted mainly of barren land without other woody vegetation besides apple orchards. Under these circumstances, a simple unsupervised classification with a subsequent supervised classification already resulted in satisfactory mapping results with an overall accuracy of 91.3%.

To our best knowledge, only Zomer et al. (2016) and Perry et al. (2009) employed coarse spatial resolution satellite data to assess TOF resources. Both used MODIS vegetation continuous fields (MODVCF) data (Hansen et al. 2003), which provide for each pixel of 250 m (Zomer et al. 2016) or 500 m (Perry et al. 2009) an estimate of percentage bare ground, herbaceous vegetation, and tree cover in their studies. Perry et al. (2009) used MODVCF data from the USA's Midwest in a comparison with ground-based forest inventory and analysis (FIA) data to point out that the FIA data are not effective in providing relevant information on TOF to the agroforestry community as a significant amount of TOF is ignored by the FIA inventory. Zomer et al. (2016) conducted a global study to assess TOF resources on agricultural land from which they concluded that 43% of all agricultural land had a tree cover of more than 10% in 2010 and that this area had increased by 2% over the previous 10 years. Both Perry et al. (2009) and Zomer et al. (2016) clearly state that the resolutions at which they conduct their analyses are too coarse to explicitly map TOF features as the uncertainties of per pixel estimates are "unacceptably high" (Zomer et al. 2016). However, both studies express confidence regarding the reliability of the general trends observed in the data.

6 Integration of Remote Sensing and Field Data

6.1 Overview

Traditionally, remote sensing data and derived map products are primarily used to assist the planning and implementation of tree inventories. With the ever-increasing availability of remote sensing data and computing power and the possibility to do retrospective analyses, remote sensing data have become an important element of REDD+ projects both for determining the baseline and for determining the results of forest emission reductions within the commitment/implementation phase. Among the main drivers for this development are increasing demands for the production of wall-to-wall maps of the variables of interest, small-area estimation for population entities where field data are not available, and the monitoring of inaccessible areas, where field data can only be made available to a limited extent. Further, remote sensing data can be used to reduce the uncertainty of population parameter estimates. And – in the absence of corresponding historical land inventories – remote sensing image archives are the only means to do land use and cover related assessments for the past. Many national geographic institutes have large archives of historical aerial photographs available for time series analyses; but it was the opening of the Landsat archive in 2008, with imagery freely available back to the early 1980s, that has triggered a multitude of studies on land cover changes over the past decades. As mentioned above, remote sensing is the only objectively verifiable data source for retrospective analyses of land cover changes, including forest cover and tree cover, even though ground truthing is an obvious challenge.

Applying remote sensing data, two broad use cases may be identified: (1) explicit application of remote sensing data for optimizing the allocation of sample locations and (2) remote sensing data as part of the inferential framework used for producing estimates of population parameters, i.e., model-assisted estimation within the design-based inferential framework or model-based inference if wall-to-wall data is available and hybrid inference if remote sensing data is only available as a sample. A combination of both use cases is possible, but the effect on reducing uncertainty might be limited if one of the two cases has already been applied (Grafström and Ringvall 2013).

6.2 At the Design Stage

A first obvious choice for the application for remote sensing data in a TOF or a general tree inventory would be to stratify the study area into forest and non-forest land; in FAO terminology, this would correspond to the three categories *forest*, *other wooded land*, and *other land*, where *other land* is the category that holds TOF. Once the land is categorized, stratified sampling can be applied using sampling and response designs specifically tailored to the different characteristics of the strata. For example, in the Indian NFI, rural areas are stratified along block, linear, and scattered tree formations, and plot designs are tailored to the average spatial configuration and tree density in the respective stratum (Tewari et al. 2014).

If available wall-to-wall data is not suitable for a proper stratification because the spatial resolution does not match the sparse TOF cover, data of higher resolution can be used in sampling schemes. This is typically done in the first phase of multiphase sampling strategies for collecting physical attributes of TOF. The information collected can either be used directly for estimating parameters such as cover percentages (Baffetta et al. 2011) or for stratifying the first-phase sample such that response designs can be adapted to local conditions (Lam et al. 2011). The latter technique is known as two-phase sampling for stratification (e.g., Särndal et al. 1992, Sec. 9.4) and has the advantage that locations without tree cover can be put into a stratum of its own and need not be visited in the field. However, a subsample of the first-phase, no-tree-cover locations might be visited in the field for verifying the classification.

One step further is the directly data-driven selection of field plot locations by using spatially balanced sampling designs, such as the *local pivotal method*

(Grafström et al. 2012). Remote sensing data are used to spread sample locations in the space spanned by the covariates to achieve samples that represent the population well with respect to the covariates. If target variables correlate well with the covariates, smaller sampling errors are achieved compared to traditional sampling designs (simple random sampling, systematic sampling, stratified sampling). Forest inventory studies have indicated a high potential of this method for increasing the precision of estimates for target variables that are related to the covariates (Grafström et al. 2014; Grafström and Ringvall 2013). For TOF inventories, experiences are missing, but the method should be generally applicable as long as TOF objects can be identified full-cover in the remote sensing data, and it is possible to extract suitable covariates. As the method is purely design-based, ordinary Horvitz-Thompson estimation is applied (Grafström et al. 2012). Further considerations on design-based sampling strategies can be found in Fattorini et al. (2015, 2016).

6.3 For Estimation

As already indicated, three broad inferential frameworks – design-based, model-based, and hybrid inferential frameworks (Ståhl et al. 2016) – can be applied for the estimation of population parameters. All three offer possibilities or depend on integrating covariates from remote sensing data that are related to one or several target variables.

Applying design-based inference, the population is assumed to be fixed, and randomness enters through probability samples that are selected according to the sampling design, which assures that each population element has a non-zero probability of being included into the sample. The population can be viewed consisting of a finite number of elements or being composed of an infinite number of points (Magnussen 2015). Uncertainty is introduced through the sampling, i.e., only a small part of the population is observed, and estimates of population parameters deviate to some extent from the population parameters but will on average correspond to them if estimators are unbiased. If models are available that relate target variables to remote sensing covariates, model-assisted estimators can be applied (Särndal et al. 1992). In general, model-assisted estimators work in a way that a first crude estimate from the applied model is corrected by an estimated total or average difference between observed and predicted values of the target variable (Ståhl et al. 2016). Estimators are typically specific to the sampling strategy applied and are available for a number of possible use cases, such as single-phase and multi-phase sampling designs, where remote sensing data is either available wall-to-wall or as a sample (e.g., Ene et al. 2016; Gregoire et al. 2011).

Under the model-based inferential framework, it is assumed that the population is generated by a random process (super-population) and the sample is considered to be fixed (Magnussen 2015; Ståhl et al. 2016). Inference is based on fitting a model to the sample values of the covariates and target variable, and uncertainty comes from errors in model parameter estimates and lack-of-fit residuals (Magnussen

2015). Model-based inference typically requires that covariates are available wall-to-wall, and it is further important to assure that the models used for inference are correctly specified (McRoberts et al. 2013) because estimates are not guaranteed to be unbiased as under design-based inference. An advantage of model-based inference is that the design used to collect field data is ignorable under certain circumstances (Magnussen 2015). This is the case for many single-phase sampling designs traditionally used in forest inventories. For example, for systematic sampling, there are no unbiased variance estimators under design-based inference, but using model-based inference, the design can be ignored and variance estimation becomes possible. However, this does not mean that field sample locations can be selected arbitrarily as such a practice would most likely lead to biased models as the variability of the population might not be covered by the sample. In this sense, model-based inference is no solution for roadside surveys. As already mentioned, models need to be correctly specified for the entire population. Anyway, a further advantage of model-based inference is the flexibility when it comes to quantifying total uncertainty of a sampling strategy that also takes the uncertainty of allometric models for biomass estimation (McRoberts et al. 2016) or additional modeling steps when combining several layers of remote sensing information (Saarela et al. 2016) into account.

The third inferential framework is termed hybrid inference (Corona et al. 2014) and has characteristics of design-based and model-based inference. Here, the remote sensing data are typically available only as a sample and not wall-to-wall and are selected in a first sample phase. In this phase, design-based principles are applied. In the second phase, field data are collected within the sampled remote sensing data, and models are applied to predict target variables for the first-phase units. Consequently, model-based principles are applied in this second phase (Ståhl et al. 2016). The two components of uncertainty, design-based error due to sampled remote sensing data and model-based uncertainty due to uncertainty in mode parameter estimates, are simply added up to yield a total error. Typical examples from forest inventory are samples of ALS flight lines (Ståhl et al. 2011b) or orbits of satellite LiDAR observations (Neigh et al. 2013) but also samples of optical remote sensing data with high spatial resolution.

Regarding TOF, no or only little experiences with the discussed estimation strategies exist. The methods are, however, general and not confined to forest inventory. Whether in TOF inventories an increased precision of parameter estimates, as reported for forest inventories, can be achieved through the integration of remote-sensing-based covariates into the estimation strategies depends on the strength of the relationships between target variables (e.g., TOF biomass) and covariates (e.g., LiDAR metrics). More research is needed on this topic.

7 Conclusions and Recommendations

Considering the rich experience gained from measuring trees and forests in almost 100 years of national forest inventories, TOF monitoring programs should not be treated isolated from forest inventories. We showed that practitioners can choose from a rich variety of possibilities with respect to sampling, response, and estimation design and that some of these possibilities are operationally applied in large-area TOF/forest assessments. Here, in particular the Indian NFI (Pandey 2008a; Tewari et al. 2014) and the national-level forest monitoring programs supported by FAO's NFMA program (Schnell et al. 2015a) are excellent examples where a holistic view on a country's tree resource is taken to overcome the often artificial divide between forest and non-forest trees.

We identified knowledge gaps on which future research should focus, namely, allometric models for volume and biomass estimation and the integration of remote sensing data, where experiences for large-area assessments of non-forest trees are missing. Concerning allometric models, most importantly more data over a wide array of growth and management conditions needs to be collected. This is essential for gaining a better understanding on how tree allometry is affected by the large variety of existing growth conditions and how this variability can possibly be captured by additional tree attributes such as crown characteristics.

Concerning remote sensing, we think that the maximum capabilities of available data for improving monitoring strategies have not yet been reached. One point for optimization is the utilization of remote sensing data in the sampling design for tailoring the response design to local conditions that may vary to a large extent in non-forest areas (density and spatial configuration of trees). Another point is the improvement of population parameter estimates by including models into the estimation design or by a data-driven selection of sample locations.

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Chapter 6
Agroforestry Practices in Temperate Regions of the World

D. R. Bhardwaj, Mansi R. Navale, and Sandeep Sharma

Abstract Temperate agroforestry systems are being practiced in the continents, like North America, Europe, highlands of the Asia, Oceania and Chile and Argentina of the South America. Distinct seasonality of the temperate regions has given rise to agroforestry practices, like windbreaks and shelterbelts, silvopastoral systems, forest grazing, woodlots, intercropped orchards and agri-horti-silviculture systems. The main tree species of agroforestry systems in the temperate parts of the world are *Pinus radiata*, *Populus* spp., *Salix* spp., *Eucalyptus* spp., *Paulownia* spp. and *Robinia pseudoacacia* and various fruit tree species, like apple, plum, apricot, peach and pear. Temperate agroforestry systems, though less diverse than tropical agroforestry systems, are playing an important role in income generation, climatic modification and biodiversity conservation.

Keywords Agroforestry practices · Temperate agroforestry · Silvopastoral systems · Windbreaks · Forest woodlots · Carbon sequestration · Biodiversity conservation

1 Introduction

Agroforestry can be defined as an "approach to land use that incorporates trees into farming systems, and allows to produce trees and crops or livestock from the same piece of land in order to obtain economic, ecological, environmental and cultural beets" (Gordon and Newman 1997; Thevathasan et al. 2004). Agroforestry has its roots in tropics or the developing countries. This is due to large population, diverse

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flora and scarce land resource, which called for a system that can combine food and wood production on same piece of land with other benefits. In other words, traditional agroforestry systems are far more numerous and widespread in the tropics, and agroforestry offers a solution to many land-use problems and constraints in those regions (Lelle and Gold 1994). Therefore, during the past two decades of organized agroforestry, developments have been much more pronounced in the tropics than in the temperate zone. In temperate regions, traditional agroforestry systems do exist where we try to link agriculture, trees and animals together to reap their multiple benefits; and solve new and old problems in these regions. However, the level of diversity in the systems is less than what is seen in tropics, but the systems are developed according to the existing natural systems. The temperate zone primarily embraces the region between latitudes of 30° and 60°. The developed countries of temperate zone, where temperate agroforestry has been developed and practiced, are North America, Europe, highlands of Asia, southern Australia, New Zealand, Chile and Argentina. Throughout this zone, the climate includes distinct warm and cold seasons. Precipitation may occur throughout the year or during either summer or winter. This seasonality has given rise to some unique agroforestry practices. Unlike the tropics, where the same crops may be produced throughout the year, individual crops in the temperate zone are generally restricted to one or two seasons, and fewer crops are grown each year. The temperate zone is also characterized by extreme physiographic diversity, ranging from dry wind-swept plains to moist rain forest conditions (Nair 1993). The different types of agroforestry systems prevailing continent-wise and their carbon sequestration potential and role in biodiversity conservation are discussed here.

2 Temperate Agroforestry Practices in Different Parts of the World

2.1 Agroforestry in North America

In North America, many agroforestry practices are being followed historically. Here, the population densities are often low and arable land resources frequently vast; hence the potential benefits of agroforestry practices are yet to be realized (Gordon and Newman 1997). Agroforestry practices that are currently being researched in North America include shelterbelts, windbreaks, silvopastoral systems, forest farming systems, integrated riparian forest systems and tree-based intercropping systems-also known as alley cropping (Thevathasan et al. 2004; Gordon and Newman 1997; Garrett et al. 2000). The various types of traditional and newly developed agroforestry systems in this continent are as follows:

2.1.1 Traditional Agroforestry Systems

2.1.1.1 Sweden System (Rotational Slash and Burn)

This system is practiced in many parts of North America. Here, fire is used to enhance forage for wildlife, to encourage berry-producing shrubs and medicinal plants and to clear underbrush to make it easier to travel, hunt and defend against enemies.

2.1.1.2 Mesquite-based System

In the deserts of south-western USA and northern Mexico, the arid-adapted nitrogen-fixing legume mesquite (*Prosopis juliflora*) is the major source of food and meets other necessities (Felger 1979; Felkar 1979; Nabhan 1982a, b; Nabhan 1985). Crops are grown with these species to take advantage of rich soil, and system provides them with food, medicine, building material and fertilizer.

2.1.1.3 Forests and Woodlots

The term "woodlot" generally refers to a small 1–40 ha privately owned forested tract, which is a part of larger property that may be farmed. These have been essential component of farming in North America. Farm woodlots and nearby woods provide variety of products to farmer including wood, fuel, sugar, nuts and berries for food and potash fertilizer in the form of wood ash. They also serve as cash reserves since they provide income, generate employment, seasonal pasture, hunting and recreational grounds. Despite their multiple benefits, these forests and woodlots were cleared after 1950s for crop and pasture production, transportation corridor and other urban uses.

2.1.2 Recent Agroforestry Systems

2.1.2.1 Windbreak Systems

Windbreaks or shelter breaks are defined as linear plantings of trees or shrubs established for environmental purposes; they have been a key practice in North America since European settlement. These are valued as shelter from harsh weather for habitats and livestock (Brandle et al. 2004, 2009). No matter where they are located, well-designed windbreaks provide economic returns and benefits to land owners. Field windbreaks are planted for protecting the fields, crops and orchards from wind, snow, etc. Similarly, livestock windbreaks are planned to protect livestock, increase feed efficiency and improve survival during cold stress periods, especially in young animals. Livestock when subjected to temperature below their comfort zone tend to increase feed intake, thus increasing costs to the farmers. Windbreaks help to maintain temperature and thus escape these costs (Kort and Turnock 1999).

Windbreaks around farmsteads help to reduce fuel demand of family and provide protection to buildings. Summer shading helps to cool houses and livestock as high temperature can lead to heat stress and stock mortality. Usually exotic species that are well adapted to specific areas are preferred for windbreaks. Exotic Norway spruce (*Picea abies*) is used as windbreaks in southern Ontario since it is not subjected to number of insect and pathological problems as compared to local species like white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) which suffer (Gordon et al. 1989) from these problems.

2.1.2.2 Silvopastoral System

A system where tree, livestock and forage are managed simultaneously is known as silvopastoral system. In North America, this system exists in various forms—those that primarily represent agriculture (trees near in pasture and orchard grazing), those that integrate agriculture and forestry (pine, pasture and cattle in south-east) and those that are solely forestry concerns (managed forest rangelands). Traditional silvopastoral agroforestry in south-east includes pine and pecan grazing and pasturing. Many agroforestry trials here focussed on cool season forages as supplement since during the warm season forages mostly die or go in hibernation during cold, thus causing scarcity (Halls et al. 1957; Hart et al. 1970; Pearson 1975; Lewis et al. 1983).

Tree species in this system that are reported to have positive growth responses to grazing are *Pinus palustris*, *P. elliottii*, *P. taeda*, *P. contorta*, western larch (*Larix occidentalis*), western white pine (*Pinus monticola*), Douglas fir (*Pseudotsuga menziesii*) and white spruce, i.e. *Picea glauca* (Sharrow 1994). Animal components of this system are sheep, cattle, goats, pigs, chickens and turkeys with pasture species, like *Paspalum notatum*, *Trifolium subterranean*, *Cynodon dactylon*, *Chamerion angustifolium*, etc. Silvopasture forest range management in north-west areas in this region had a negative impact on young seedlings, which leads to soil compaction. However, these problems are being addressed by closing grazing for some period, restricting livestock from the seedlings areas. Nowadays, recent research is focussed on use of livestock for competition control and site preparation. In south eastern British Columbia, sheep and cattle have been used to trample, consume and otherwise reduce the vigour of competing vegetation to prepare site for plantation (Timberman 1975; Wood 1987). This practice has been found cheaper than the use of machines and reduces site disturbance and soil erosion and is suitable to inaccessible areas. Tree shelters and slurry spraying have been used in some areas to protect trees in silvopastoral systems from trampling and destruction by the livestock in mid-west and north-east areas.

2.1.2.3 Alley Cropping

It consists of planting trees at spacing that allow crop cultivation between the rows. In temperate systems, alley-crop fruit tree-type association is commonly seen, and it also yields maximum benefits to farmer. Intercropping native trees with crops is feasible in many areas in North America; however, most intercropping research and establishment have utilized black walnut (*Juglans nigra*) as the tree species of choice. The walnut-based system delivers multiple benefits, like nuts, weed control in rows and microclimatic modifications. However, new tree-crop combinations are being studied and planted. These include *Albizia julibrissin* with grain sorghum in summer and wheat in winter at Georgia, poplar (*Populus* spp.) and spruce (*Picea glauca*) in Canada and black locust (*Robinia pseudoacacia*) and barley in southern Ontario (Rhoades et al. 1998; Peichl et al. 2006; Ntayombya and Gordon 1995).

2.1.2.4 Integrated Riparian Management Systems

Agriculture activities seem to have adverse impacts on waterways especially in eastern North America. In many areas, riparian forest systems are being removed to create space for agriculture and cattle resulting in erosion and loss of organic matter inputs. Hence, agroforestry system that is profitable and shows the promise in rehabilitating these waterways is being developed and adopted as an integrated riparian vegetation management system. These systems mediate with environmental problems and provide fish and wildlife habitat when managed correctly.

These are transitional systems between uplands and river, lakes or ponds. The main tree species of riparian waterways include black cherry (*Prunus serotina*), black willow (*Salix nigra*), white pine (*Pinus monticola*), persimmon (*Diospyros* spp.), red maple (*Acer rubrum*), red oak (*Quercus rubra*), river birch (*Betula nigra*), white oak (*Quercus alba*), willow oak (*Q. phellos*), etc. Tree arrangement is linear in shape characterized by flowing water that rises and falls at least once within the growing season (Lowrance et al. 1992; Welsh 1993). The diverse species mixture in this system displays maximum carbon sequestration potential as compared to monocropping. In Iowa, an interdisciplinary study has investigated the multiple benefits of stream rehabilitation using multispecies riparian buffer strips. In a five-year study, results indicated diminished concentration of both atrazine and nitrate-N in stream waters along with other benefits (Isenhart et al. 1996; Rodrigues 1996; Schultz et al. 1996). These systems store C in both above and below ground biomass of vegetation and soils.

2.1.2.5 Forest Farming Systems

Forest farming systems involve utilizing existing forested or wooded areas to produce timber and other economically valued products on regular or annual basis. Examples of forest farming include production of honey, aromatics, craft material, fence posts, medicinal plants, mushrooms, pine straw, sap, syrup, etc. When these products are obtained from forests which have been properly managed to have quality in these products, they constitute agroforestry. In many parts of North America, farmers are seen to follow this system for production of maple syrup from maple (*Acer* spp.) and ginseng (*Panax ginseng*) cultivation, and shiitake mushroom (*Lentinula edodes*) on wood logs.

2.1.2.6 Biomass Production and Plantation Forestry Systems

Plantation forestry is a practice that has a potential to rehabilitate degraded agricultural land in North America. Cultured trees are grown on formal agricultural sites to improve soil structure, increase organic matter content, slow erosion and improve nutrient status. Biomass production systems include energy production from forest biomass or waste or biomass production on large scale by short rotation forestry (Smith 1982). The species that are planted are poplars and hybrid willows. These species have been used in intercropping too. Another important role of biomass production system is their use for disposal of nutrient-rich materials, like municipal sewage sludge or livestock manure (Colletti et al. 1994), potential to reduce salinity of irrigation water (Cervinka et al. 1994), etc.

2.1.2.7 Homegardens/Forest Gardens

This system consists of three to four vertical layers of trees and shrubs (Jacke and Toensmeiier 2005). These are relatively small area up to 0.1 ha, and elements are managed intensively for water, space, nutrient and sunlight. Feldhake and Schumann (2005) experimented a multi-strata system of 1.2 ha area planted with Chinese chestnut (*Castanea mollissima*), pawpaw (*Asimina triloba*), hazelnut (*Corylus avellana*) and white pine (*Pinus monticola*) and interplantings of black and blue berry (*Rubus* spp.) in central Appalachia, USA, for its potential in generating income. The study results indicated that such system overcomes the limitation of nutrient loss, thus maintaining the nutrient content in soil by increasing its nutrient retention capacity.

2.2 Agroforestry Practices in New Zealand

New Zealand is a pioneer country in the study of silvopastoral systems in temperate regions. These systems were first recognized in 1969 as a potentially profitable land use, and since then, many trees of several species have been established on farms (Hawke and Knowles 1997). Agroforestry here encompasses the conversion of pastoral land to forestry with understorey grazing particularly in the first half of the rotation. *Pinus radiata* is the most common and preferred species in agroforestry systems due to its high profitability, covering over 90% plantations. Agroforestry systems in New Zealand exist in three distinct types—the planting of trees to existing pastures and managing them under a direct saw log regime, grazing in plantation forests, and planting and management of shelterbelts. The detailed structure and potential of these systems are as follows.

2.2.1 Trees on Pastures

Tree species are hand-planted due to steep terrain and intensive grazing is carried out before plantation. White clover (*Trifolium repens*) and rye grass (*Lolium perenne*) are the pasture species in these systems. Radiata pine (*Pinus radiata*) is 20–30 cm high when planted and grows to 50–150 cm height in first growing season. This rapid tree growth favours radiata pine planting since it reduces tree damage by browsing animals. It also produces protective sheet of resin on debarking injuries hence decreasing any significant loss. One of the objectives of this system is to produce good saw logs at lowest cost and shortest time. For this, efficient pruning and thinning of trees are done at proper intervals. Species like willows and poplar are also being planted in pastures. Percival and Hawke (1985) observed that livestock-carrying capacity decreases with increasing tree age and stocking because of decreased pasture production and accumulation of thinning and pruning debris in case of radiata pine-planted pastures.

McElwee and Knowles (2000) modelled a curvilinear relationship between pasture production and canopy closure for *Populus* plantations, and the predicted extinction point occurred later for *Pinus radiata*, at 85% of canopy closure. Reason suggested was poplar being deciduous allowed more period of full light penetration to ground thus promoting the pasture growth or that non-light-related competition is greater under *P. radiata* stands than *Populus* ones. Soil physical properties monitored on a pasture with radiata pine indicated greater water retention, less bio-pore and lower saturated hydraulic conductivity than soil in open pasture. It has been widely shown that there is an increase in carbon (C) and nitrogen (N) mineralization under trees compared to open pastures (Giddens et al. 1997; Parfitt et al. 1997; Amatya et al. 2002), particularly near the surface.

2.2.2 Forest Grazing

Plantations in New Zealand have a history of being used for grazing by cattle and sheep. This method offers supplementary feed to adjacent farms in winter; however, this has also increased access for pruning and thinning operations. The plantations of North Island had become heavily infested by pampas grass, and grazing has helped to reduce this; however this species have nutritional values. So, the practice of sowing grasses and forage legume has been encouraged in plantations. The result of extensive field sowing and trials in forest stands have indicated “Maku” lotus (*Lotus uliginosus*) has outstanding characteristics for forest grazing (Gadgil et al. 1986; Lowther and Barry 1985).

2.2.3 Belts of Trees (Shelterbelts)

These have been the feature of lowlands in New Zealand; they reduce wind speed and provide protection to lambs. Many timber species have been used most common being the radiata pine. Trials on sheltered pasture were conducted in the Canterbury plains in the mid-1980s and 1990s. In Canterbury, a 60% improvement in dryland pasture was observed in sheltered areas over 3-year periods (Radcliffe 1985). Recent research recorded shelterbelt as a profitable enterprise and major timber source for the future.

2.3 Agroforestry in Australia

Agroforestry as a measure to increase farm income and profit is well recognized in temperate Australia, and research has been going on for the past 20 years. Land degradation by reducing tree cover has led to dryland salinity, soil wind erosion, soil acidification and soil structure decline. Farmers looking for means to diversify their income and reduce land degradation have found solution in agroforestry (Moore and Bird 1997).

2.3.1 Scattered Trees on Pasture

This was the first type of agroforestry system seriously implemented in Australia. The system having combination of wide-spaced pine trees with sheep grazing was found to give 30% more production as compared to pure systems (Anderson et al. 1988). One of the benefits of trees on pasture practice is production of saw logs in areas too dry (<600 mm rainfall) for plantations, since most of the temperate Australia receives less than this amount of rain. Species planted in this system are *Eucalyptus saligna*, *E. maculata*, *E. globulus*, *E. diversicolor*, *Pinus radiata* and *Casuarina cunninghamiana*. Eucalyptus has advantages over pine since it has tendency of self-pruning, making it cheaper and easier to prune. Studies indicated complex interaction between tree and pasture species in this system (Moore and Bird 1997). Scattered trees also need conservation since they provide ecosystem services that are essential for farming (Manning et al. 2006).

2.3.2 Belt of Trees (Shelterbelt)

This system involves widely spaced trees of three to six rows, separated by wide pasture practice by farmers. The objective of this arrangement is to reduce wind erosion and provide shelter to livestock, crops and pasture. The distance between belts differs with objective of farmer. In Esperance, Western Australia's south coast, farmers plant belts of two to three rows of pine about 200 m apart to prevent wind erosion and protect crops, pasture and livestock. In Western Australia, the popular spacing is about 25 m between two and four belts for wood production and shelter to pasture land. To carry on agricultural activities, distance of 20 m or more between belts is preferred. Studies have shown that agroforestry practice reduces groundwater tables and hence can help to combat salinization due to waterlogging. A study in Western Australia over a 7-year period depicted that groundwater level decreased more in agroforestry area as compared to pure pasture (Bari and Schofield 1991). This system also increases crop and pasture yields by sheltering them from wind.

2.3.3 Woodlands

In this system, trees are planted in blocks on slopes to use excess water and combat soil erosion or on the inaccessible areas or on farm where cropping is not possible. The objective of this system mainly is wood production. The main species planted in blocks are radiata pine (*Pinus radiata*) and maritime pine (*Pinus pinaster*) for softwood saw logs and *Eucalyptus globulus* for pulpwood. *Eucalyptus saligna*, *E. maculata*, *E. botryoides*, *E. viminalis* and blackwood (*Acacia melanoxylon*) are planted for hardwood saw logs (Reid and Wilson 1985). After planting trees, grazing management is done for protection from livestock. Thinning and pruning operations are carried out aimed at production of high-quality timber.

2.4 Agroforestry in Europe

European landscape has undergone significant changes; around three centuries ago, there were still agroforests here because many high-value trees from forest were retained during land clearing. This retention was done to obtain various products from these trees, like oaks for acorns, beeches for mast, lopped ashes for fodder and fruit trees of Rosaceae family. These trees provided shelter, fodder, timber, fuelwood, etc. However, intensification, specialization and mechanization of agriculture resulted in elimination of trees from fields. Remnants of practice of trees on fields are seen in Mediterranean zones (Dupraz and Newman 1997). Various prevailing agroforestry practices in this continent are following:

2.4.1 Dehesa System

Dehesa is one of the oldest and traditional agroforestry systems in Iberian Peninsula, Europe. It covers an area of about 2 million ha. This practice is characterized by savannah-like landscape setting with sparsely populated oaks (20–50 ha^{-1}), allowing grazing of livestock. The main oak species include *Quercus ilex*, *Q. suber*, *Q. faginea*, etc. The space between trees is used for growing crops like barley and wheat (Joffre 1988). Trees provide fodder for livestock, fruits for human consumption and ecological benefits, like soil fertility, soil stability, water retention, etc.

2.4.2 Forest Grazing

It consists of large plots of lands with trees that are privately owned. Broadleaved trees exist in this system, especially oaks. Sheep grazing is common but deer are also found in some areas. Many montane and Mediterranean forests are still grazed in Europe. Traditional forests have low fodder production; among the best producers are larch groves (of *Larix decidua* trees) in southern French Alps and Scots pine forests in central France (de Montard 1988). The major problem in trees on fields or pasture is damage by browsing animals in early stage which leads to death. Much research has been carried out on this matter and tree shelters are developed. Tree shelters are tall plastic tubes 1.5–2.5 m tall dependent on slope and cattle type in that area. Seedlings are placed in these shelters and by the time seedlings grow out of shelter, it is out of reach to animals.

2.4.3 Intercropped Orchards

Orchard intercropping dates to Roman Empire in the first century BC when wheat was intercropped with olive (*Olea europaea*) trees. Wheat cultivation curbed vegetative growth of olive thus increased its fruit production (Lelle and Gold 1994). In the present day, orchard intercropping trees that are being used include walnut (*Juglans nigra*), almond (*Prunus dulcis*), peach (*P. persica*), apricot (*P. armeniaca*) and olive (*Olea europaea*) trees. Carob (*Ceratonia siliqua*) trees are intercropped with cereals in Spain, Greece and Cyprus. In Mediterranean areas with heavy autumn rainfall, perennial grasses are intercropped in orchards and vineyards, which prevent soil erosion losses and improve fruit quality by competing for water resources (Baldy et al. 1993; Moulis and Guillerm 1994). Intercrops in this system include maize, sorghum, winter cereals (durum wheat, wheat and barley), soybean, canola, sunflowers, fodder crops like alfalfa and aromatic crops (lavender).

2.5 Agroforestry in South America (Argentina)

The Andean Patagonian forests in Argentina are located between 37°S and 55°S and are site of major silvopastoral activity, i.e. forest grazing. Species like *Nothofagus antarctica* and *N. pumilio* are found in these forests. These forests have been degraded due to overgrazing and tree damage resulting in depletion of natural resources. The main herbage forage species are *Poa pratensis*, *Holcus lanatus*, *Trifolium repens*, etc. The major agroforestry practices followed in this area are following:

2.5.1 The Nomadic System

In northern and central Neuquen region, Argentina, the practice includes grazing of herds of sheep, goat and cattle in arid steppes during cold weather and moving them towards forests and neighbouring meadows during summer.

2.5.2 The Continuous Grazing System

It consists of year-long grazing in forests, meadows and steppes and occasional browsing of forest plant species.

2.5.3 Seasonal Grazing

Grazing is seasonal, in forest steppes during winter and in higher elevation forests during summer. Afforestation has been started in Patagonia Mountain with fast-growing species, like pine, eucalyptus, etc. Diversification is needed to increase income and restore degradation; hence silvopastoral use and wood production from native forests are being considered as sound alternative with ecological benefits.

2.6 Agroforestry Practices in Asia

2.6.1 Temperate Agroforestry Systems in China

China has developed numerous agroforestry systems since the 1950s; some of these existed from centuries. These have resulted in long-term adaptation of local plants and cultural techniques to local conditions especially in temperate zone. In temperate region, most common system is silvi-arable in nature, intercropping and farmland shelterbelts. The primary agroforestry practices followed nationwide include homegardens and trees along canals, roads and houses in villages. The land available to a farmer in China is on an average only 0.1 ha; hence it is considered precious and intensively managed. Agroforestry is considered a land use system that can provide multiple benefits along with protecting land from degradation. Agroforestry varies zone to zone based on climate and soils, for example, system using forest and understorey medicinal plants is practiced more in cold temperate zone, while windbreaks, shelterbelts, sand fixation and silvopastoral systems are more common in north.

2.6.1.1 Silvi-arable Systems

These systems predominate in northern China. Coniferous species, basswood, willows and birch are grown with understorey of medicinal plants, like schisandra (*Schisandra chinensis*), acanthopanax (*Eleutherococcus* spp.), Chinese cranberry

(*Oxycoccus* spp.), rhododendron (*Rhododendron* spp.), oplopanax (*Oplopanax horridus*), etc. along with vegetables or grains. Fruit trees, like *Lycium* spp. and *Prunus* spp., are also used for intercropping. The pasture-hedge system is a very promising system in north-west China and northern regions. *Paulownia*-crop intercropping is the important and successful system in this type. The most common species in temperate zone is *Paulownia elongata*, and understorey crops planted are winter wheat, oilseed rape, garlic, cotton, soybean, millets, peanuts, sweet potato, vegetables, melons and medicinal herbs.

The most ideal intercropping crop is winter wheat. The branch and leaf arrangement of *Paulownia* is such that leaf emerges late in April and leaf fall late in November. This sparse arrangement helps in maximum light penetration to lower canopy, and late leaf fall protects the undergrowth from harsh winter. The deep root system does not compete for nutrients with crops, and this species is considered most suitable for multipurpose agroforestry practices (Zhu et al. 1986; Zhu 1991; Wu and Dalmaico 1991). Pasture-hedge system is another promising system in north-west China. Fencing provides protection to pasture and improves ecological environment and productivity. The tree species normally used are indigenous, highly resistant to pests, fast-growing and easily coppiced like sea buckthorn (*Hippophae rhamnoides*), Russian olive (*Elaeagnus angustifolia*) and nitraria (*Nitraria retusa*). Pine forest can also help as pasture, as the pine needle powder contains essential nutrients like calcium, phosphorus, crude protein, fat and crude fibre. It acts as chicken feed additive, which increases egg production and disease resistance. It stimulates growth in pigs and increases milk production in cattle (Wang 1991).

2.6.1.2 Fruit/Nut Intercropping Systems

Chinese date (*Ziziphus jujuba*) fruit is an indigenous species, which has been intercropped with crops for over 600 years. The main intercrops used are wheat, maize, soybean, peanuts, cotton and vegetables; however, date-wheat is the ideal model. Date leaf emergence is late so wheat receives maximum light, and when leaf emergence starts in date, wheat is in heading stage and needs only 20–30% light hence positive interaction for coexistence. Research has shown that date trees modify microclimate in field and protect from wind. In mountainous region of China, 80% of arable lands are slopping, and slopes are greater than 25%. The contour hedgerow cropping first tested in the Georges region of China is now widely used in these mountainous regions. These systems reduce soil loss by runoff and use of N-fixing species in this system has reported enhancement of soil fertility, nutrient levels and organic matter (Sun et al. 2008).

2.6.1.3 Four-side Plantations/Homegarden Forestry

This system consists of planting of trees along roads, rivers and canals and around houses and villages, especially those that occur in plain areas. Trees are planted in combination with annual crops, vegetables or animals. This system is referred to as homegarden forestry when present around houses. The main timber species are paulownia (*Paulownia elongata*), poplar, black locust (*Robinia pseudoacacia*), toona (*Cedrella toona*) and willows (*Quercus* spp.), while fruit trees are nut trees, date palm, persimmon, walnuts, apple, plum, apricot, peach and pear. Intercropping of field crops is done with these tree species. Trees act as a fence for chickens during summer and protect them from diseases. Roadside-planted trees serve as an important source of timber also (Wu and Zhu 1997).

2.6.1.4 Shelterbelts

Extensive farm woodlots of *Populus simonii* are raised on farmland for construction in temperate regions of China (Richardson 1966). The most effective shelterbelts are a narrow belt with two to four rows of trees with 5 m width and wind coefficient of 0.4 to 0.5. Orientation is south-north and east-west with area of 10 ha. Poplar is common species for shelterbelts with another shrub species. These modify microclimate, protect from hailstorms and wind, stabilize crop production and provided timber and fuelwood.

2.6.1.5 Tree-Crop-Fish

This system includes trees, like paulownias, willow, poplar and fruit trees, along ponds in which fish is cultivated. Crops raised are wheat, oil crops, vegetables and herbs (Wu and Zhu 1997).

2.6.1.6 Mulberry-Crop-Silkworm

Mulberry (*Morus alba*) is raised for silkworm rearing along with wheat, peanuts, beans and vegetables (Wu and Zhu 1997).

2.6.2 Temperate Agroforestry Systems in India

India, with its diversified climate, experiences both tropical and temperate conditions. Northern India falls in temperate zone consisting of western Himalaya and eastern Himalaya regions which includes states, like Kashmir Valley, Himachal Pradesh and Uttarakhand. A wide range of agroforestry systems have been developed and practiced in these regions.

2.6.2.1 Traditional Agroforestry Systems

2.6.2.1.1 Boundary Plantations

Boundary plantation is one of the oldest planting patterns practiced on paddy fields. Trees are grown along road or canal passing by the rice field. Species planted are *Salix*, *Populus deltoides*, *Populus nigra* and *Aesculus indica* (Mughal and Khan 2007).

2.6.2.1.2 Kitchen Garden

It is practiced throughout the area and is located around residence. Fruits and vegetables are grown in one part along with poultry being reared on same area. Tree and vegetable species are similar as in above systems and planted according to the preference of the farmer.

2.6.2.1.3 Agri-silviculture on Sloping Lands

This system is practiced in hilly areas by people residing either at the mid-mountains or foothills of mountains. Trees are planted on boundary as well as scattered in the field to offer protection from heat, evaporation and soil loss. Crops like mustard and vegetables such as brassica, carrot, radish and turnip are grown. Trees planted are *Robinia pseudoacacia*, *Ailanthus excelsa*, *Populus nigra* and *Salix alba* (Mughal and Khan 2007).

2.6.2.2 Newly Developed Agroforestry Systems

2.6.2.2.1 Agri-silviculture

This system combines production of crops, trees and/or shrubs to obtain various products, like food, fuel, fodder, small timber, etc. The tree species when managed using proper silvicultural techniques provide security against adverse climatic factors, supplement the income, enrich soil fertility, improve nutrient recycling and increase crop productivity. This system is more sustainable than mono-cropping system as this system provides economic and ecological benefits (Verma and Bhardwaj 2007).

A type of this system is medicinal agroforestry; here medicinal plants are grown with multipurpose trees. Poplar is one of the tree species that has been tested suitable for these systems. The research and information generated over the years have proved that cultivation of high-value cash crops (HVCC) with multipurpose tree species, especially timber, is a profitable alternative for traditional cropping systems. The economic analysis indicated benefit-cost ratio between 1.5 and 2.4 for medicinal agroforestry system (Thakur and Thakur 2002).

2.6.2.2.2 Agri-horticulture

In this system fruit trees are grown with agricultural crops. For example, fruit trees apple (*Malus domestica*), apricot (*Prunus armeniaca*), plum (*P. domestica*), peach (*P. persica*), nectarine (*P. Persica* var. *nucipersica*), litchi (*Litchi chinensis*), walnut (*Juglans regia*), almond (*P. dulcis*) and pomegranate (*Punica granatum*), along with field crops, like tomato, cabbage, cauliflower, maize, wheat/mustard and beans (Verma and Bhardwaj 2007).

2.6.2.2.3 Agri-silvi-horticulture

This system combines production of agricultural crops, forests and fruit trees. Tree species are selected according to agroecological zones. In this system forest trees are mainly retained for household needs and other services, while fruit trees are for income generation.

2.6.2.2.4 Silvopastoral

This system combines production of fodder trees and grasses/forage crops and/or animals. It helps to maintain higher productivity in a sustained manner at relatively low input levels even on poor soil strata. Tree species preferred are *Grewia optiva*, *Morus alba*, *Bauhinia variegata*, *Dalbergia sissoo*, *Populus deltoides*, *Albizia chinensis*, *Terminalia arjuna*, *Sapindus mukorossi*, *Terminalia bellirica*, *Terminalia chebula*, *Santalum album*, *Aegle marmelos*, *Celtis australis*, *Quercus leucotrichophora*, *Q. dilatata*, *Robinia pseudoacacia*, etc. The common grass species are species of *Eragrostis*, *Apluda*, *Chrysopogon* and *Poa* (Verma and Bhardwaj 2007). Intercropping of *Amorpha fruticosa* and oats is an example of such system. This system exhibited land equivalent ratio (LER) of more than one which proves that system is better than sole cropping. Mughal and Makaya (2000) have also identified silvopastoral system as best system in degraded areas to overcome fodder scarcity and stabilization of the degraded areas.

2.6.2.2.5 Pastoral-silvi-horticulture

This system means cultivation and management of grasslands supporting forest and fruit trees simultaneously on same piece of land. The perennial in this system provides the fodder or functions as live fences around grazing land or is retained as commercial, shade, browse and fruit trees.

2.6.2.2.6 Energy Plantations

In this system, short-rotation fast-growing tree species are grown on marginal lands, like mined-out lands, riverbanks, lands with impeded drainage, roadside landfills, farm boundaries and uncultured zones of agricultural fields. These trees are grown to meet energy demands of rural masses. Species preferred under this system are

Eucalyptus tereticornis, *Melia azedarach*, *Leucaena leucocephala*, *Acacia mollissima*, *Eucalyptus hybrid*, *Salix* spp., *Morus* spp., *Alnus* spp., *Albizia procera*, *Bambusa* spp. and *Albizia lebbeck*.

2.6.3 Temperate Agroforestry Systems in Nepal

Nepal is a landlocked country in South Asia lying between latitudes 26° and 31°N and longitudes 80° and 89°E. It has five climatic zones, broadly corresponding to the altitudes. The tropical and subtropical zones lie below 1200 m, the temperate zone between 1200 and 2400 m, the cold zone between 2400 and 3600 m, the subarctic zone between 3600 and 4400 m and the Arctic zone above 4400 m. It is commonly divided into three physiographic areas: mountain, hill and terai. The traditional and newly developed temperate agroforestry systems (Joshi 2011) are as follows.

2.6.3.1 Traditional Agroforestry Systems

2.6.3.1.1 Taungya

Taungya agroforestry practice was first started in Nepal in 1972 in Tamagadhi of Bara district, where forest areas encroached by the hill migrants were planted and given to encroachers to grow agricultural crop. The main aim of this practice was to protect remaining forests from encroachment.

2.6.3.1.2 Agri-horti-silvopastoral System

Traditional agroforestry farming system of Nepal includes growing of trees, agricultural crops and livestock for subsistence livelihood, which is then gradually replaced by the cash crops.

2.6.3.1.3 Agri-horti-silvi System

The tree-crop combinations found are cardamom under uttis (*Alnus nepalensis*), ginger and turmeric under tree shade and homegardens, coffee under ipil-ipil (*Leucaena leucocephala*) and shade trees and tea under sissoo (*Dalbergia sissoo*) and siris (*Albizia lebbeck*) and vegetables and fruits (orange, banana, papaya, mango, apple, etc.) for commercial purposes.

2.6.3.2 Newly Developed Agroforestry Systems

The newly developed agroforestry systems for the high mountain and mid-hills of Nepal are homegardens, agri-silviculture system, silvopastoral system (local name *kharbari*), agri-silvopastoral system (typical hill farming, in which agricultural crops are grown on terrace flat, trees on terrace bunds and borders and grasses on terrace slopes—*kanla*) and alley cropping.

2.6.3.2.1 Agri-silviculture System

This system is common in all agroecological zones of Nepal. In this system, agricultural crops are grown in terrace flat, and trees are grown in terrace bunds, borders and slopes. Trees grown in hilly regions are mainly fodder trees such as *Artocarpus lakoocha* (badahar), *Bauhinia purpurea* (Tanki), *Bauhinia variegata*, *Leucaena*, mulberry, etc. in hills and fodder trees such as *Saurauia nepalensis*, *Litsea monopetala*, etc. in plains.

2.6.3.2.2 Silvopastoral System

This system is common in all agroecological zones of Nepal, where land is marginal for crop production. In mid-hilly region, land having grasses is known as *kharbari*. Trees grown in *kharbari* in different regions of Terai are sissoo, eucalyptus, ipil-ipil, etc. In hills, common fodder tree species are *Artocarpus lakoocha*, *Bauhinia purpurea*, *Bauhinia variegata*, *Leucaena*, etc., and timber species like *Schima wallichii* (Chilaune) are raised, whereas in mountains fodder trees such as *Saurauia nepalensis* (Gogan), *Litsea monopetala* (Dudhilo), *Quercus semecarpifolia* (Khasru), etc. are the common species.

2.6.3.2.3 Agri-silvopastoral System

This is typical hill farming system of Nepal, in which agricultural crops are grown in terrace flat, trees in terrace bunds, borders and slopes and grasses in terrace slopes, and some farmers have been growing improved legume and nonlegume grasses such as Mott Napier (*Pennisetum purpureum*), setaria (*Setaria splendida*), mulato (*Brachiaria brizantha* × *B. ruziziensis*) and forage peanut (*Arachis pintoi*) along terrace bunds and borders.

2.6.3.2.4 Agri-horti-silviculture

This system is common in homegardens of mid-hills, Terai and inner Terai of Nepal, where fodder trees such as *Artocarpus lakoocha*, *Bauhinia purpurea*, *Leucaena* spp., etc. and timber and firewood species such as sissoo, eucalyptus, baikaino, etc. are grown around fruit orchard that acts as shelterbelt and agricultural crops such as ginger, turmeric, yam, colocasia and vegetables are grown under fruit trees.

2.6.3.2.5 Homegardens

This system is common in both hills and Terai belt of Nepal. Tallest trees (fodder trees in hills) of this system are strong light demander, and middle-storey trees are moderately shade-tolerant fruit trees. At the ground level, vegetables and other herbaceous shade-tolerant crops like ginger, turmeric, chilly, pineapple, coffee, cardamom, etc. are grown under tree shade.

2.6.3.2.6 Multipurpose Tree Species

Multipurpose tree species (MPTs) are those species which give multiple products, such as fruit, fodder, fuelwood, timber and medicines. The main MPTs of hilly region in Nepal are chiuri (*Bassia butyracea*), badahar (*Artocarpus lakoocha*), ipil-ipil (*Leucaena* species), kimbu (*Morus alba*), etc.

2.6.3.2.7 Alley Cropping

It is also known as hedgerow intercropping and involves managing rows of closely planted woody trees with annual crops grown in alley in between hedgerows. Woody plants are cut regularly, and leaves and twigs are used as mulching materials on the alley cropping areas for reducing evaporation from soil, controlling weeds and adding nutrients and organic matter into the soil. Increase crop yield due to the addition of organic matter into the soil.

Plants (*Leucaena* spp., *Bauhinia variegata*, etc.) are grown on the hedgerows which fix nitrogen into the soil. Hedgerows give products like fruit, fodder, leaf litter, fuelwood and poles. This system is generally practiced in slopping lands, which helps in reducing soil erosion. The position and spacing of hedgerows and crop plants in alley cropping system depend on plant species, climate, slope, soil condition and space required for the movement of people and tillage equipment. The tree species grown in this system are *Leucaena* spp., *Gliricidia sepium*, *Calliandra*, *Sesbania sesban*, *Artocarpus lakoocha*, *Morus alba*, etc., with crops like maize, rice, wheat, finger millet, black gram, mustard, barley, potato, peas, etc.

3 Carbon Sequestration Potential of Temperate Agroforestry Systems

Rising levels of atmospheric carbon dioxide and associated global warming have moved to the centre stage of climate change discussion. Silvopastoral system is the most widely adopted system in temperate regions. In North America, this system recorded the highest C sequestration potential than other agroforestry systems and is the most common system in the region. These systems outperform grassland and forest since they have C capture mechanism of both systems that maximizes C sequestration above and below ground. In general, trees store about 50–60% of C above-ground, whereas the pastures store 10% above-ground, the rest being allocated below ground (Houghton and Hackler 2000; Sharrow and Ismail 2004). The roots of perennial vegetation in silvopastoral systems shift C deeper to soil profile compared to conventional pasture or row crops. Strategies to enhance C sequestration in this system may include selection of complementary tree, shrub and pasture grasses with optimal biomass accrual, deep rooting habits and greater below ground C accumulation potential.

In Canada, Gordon and Thevathasan (2005) reported the importance of using fast-growing species in silvopastoral systems to reduce C emissions; they estimated that net C sequestration of a poplar-based silvopastoral system was three times more than that reached by a monoculture system. In Chile, the net carbon sequestration values for silvopasture and prairie were reported to be 3.8 Mg C ha^{-1} and 1.09 Mg C ha^{-1}, respectively. Study by Dube et al. (2011) in Chilean Patagonia reported that adoption of silvopasture system can be a sustainable land management practice that can preserve and increase soil C pools and can contribute to reduction in atmospheric CO_2 and permit to offset GHG emission from animal grazing and fertilizer application. Thus, it has potential to convert the entire region into effective C sinks than C sources.

Windbreaks, like other agroforestry practices, have a great promise for C sequestration (Schoeneberger 2009). They are planted in temperate areas for protection from wind and snow. In addition to C sequestered by trees, windbreaks provide additional C sequestration due to improved crop and livestock production and energy savings (Kort and Turnock 1999). High rate of soil C sequestration and high SOC were observed in windbreaks of North America; this was attributed to the absence of soil disturbance, increased litter inputs, reduced erosion and deposition of windblown material.

In Germany alley cropping system with *Robinia pseudoacacia* has received considerable interest as an alternative to monocropping since it provided additional wood source and acted as potential C sink to counterbalance growing GHG emissions (Quinkenstein et al. 2011). These systems have come in to focus for reclamation of post-mining areas where initial content of SOM is generally zero and soil fertility very low (Nii-Annang et al. 2009). The increase in SOM in reclaimed areas depends upon amount of biomass production and return to soil as well as mechanisms for C protection and retention. Due to its high potential for litter fall production and nitrogen fixation, *R. pseudoacacia* improve soil physical, chemical and biological properties by increasing SOM, thereby converting mine spoils into productive and sustainable lands.

In riparian systems of North America, C sequestration is more in the aboveground component. The tree density and basal area of riparian buffer are almost like forests. Biomass and thus C stock increment in riparian buffer increased up to certain period and later increased at diminishing rate and finally flattened down. About 90% of the accumulation was completed in 20–40 years (Balian and Naiman 2005). The vegetation with trees and grasses has more fine and medium roots which trap C and help in its sequestration than another crop systems (Tufekcioglu et al. 1999; Marquez et al. 1999). Soil C stock is also higher in mature riparian than monocrop or younger riparian system as the roots die and C gets fixed in soil (Giese et al. 2003).

The soil represents the important pool of C storage in terrestrial systems, accounting for about 75% of total stored C (Lal 2005; Dresner et al. 2007). Soil C sequestration depends on the edapho-climatic conditions, which may increase or reduce organic matter inputs, incorporation of organic matter into soil and organic matter mineralization (Neider et al. 2003). Temperature and humidity are the main drivers of soil organic matter (SOM) production, incorporation and mineralization (Theng et al. 1989). If these are optimal for above-ground biomass production, the inputs of organic matter to soil are also high thus resulting in high SOM. In the dehesa system in Mediterranean area, presence of mature trees and, therefore, the rate of incorporation of their residues are associated with higher SOM levels below the tree than away from the tree in agroforestry system established under trees without canopy closure (Moreno and Obrador 2007).

4 Temperate Agroforestry and Biodiversity

Agroforestry systems tend to be more biologically diverse than conventional croplands, degraded grasslands or pastures and early stages of secondary forest fallows. The use of native species in agroforestry systems will provide greatest benefits to biodiversity. It can augment supply of forest habitat and enhance connectivity. This can facilitate migration of species in response to climate change (SCBD 2003).

Adoption of various agroforestry systems in North America has positively affected the biodiversity and wildlife there. The natural fence line and planted windbreaks interrupted the monotony of the landscape and added diversity to agricultural landscape. Studies indicated that more diversity of fauna was found in agroforestry field than mono-cropped field (Williams et al. 1996). Windbreaks provided refuge to pest and beneficial organisms, and studies have suggested positive benefits, by these biocontrol agents on insects and pests. Alley cropping in slopping areas promoted terracing and organic matter build-up, thus reducing degradation. Birds associated with the field edges undoubtedly help to reduce insect pest problems. Apart from production benefits, agroforestry systems provide different other ecological benefits. For example, intercropping system can be used to promote terracing and organic matter build-up in soils on the slopping lands, windbreaks can provide transportation corridors between disparate woodlots for wildlife, and silvopastoral systems can provide relief to animal component from the throes of extreme weather. Agroforestry, particularly belts of trees, where timber and shelter are products, has become important strategy in development of sustainable methods of land use in Australia. Wu and Zhu (1997) reported that the existing agroforestry systems in China show harmony with the natural environment and play important roles in modifying microclimate, improving environmental conditions, minimizing natural disasters, preventing soil erosion and preventing desertification.

5 Conclusions

Temperate agroforestry systems are mainly prevailing in the developed countries of the world. These systems, like windbreaks and shelterbelts, silvopastoral systems, forest grazing, woodlots, intercropped orchards and agri-horti-silviculture systems show harmony with natural environment are directed towards providing indirect benefits. These indirect benefits include playing ground to animals, soil and water conservation, C sequestration, timber supply, protection of agriculture landscape against snow and windstorms and biodiversity conservation. This is in addition to supply of directs benefits, like timber, fuel, fodder, fruits, etc.

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Chapter 7
Agroforestry Systems in Northern Spain: The Role of Land Management and Socio-economy in the Dynamics of Landscapes

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Abstract Agroforestry systems in northern Spain are, for the most part, high nature value (HNV) systems in biodiverse landscape mosaics. These systems, frequently linked to livestock grazing, have evolved drastically over the past 50 years, primarily due to various socio-economic drivers affecting the landscape structure and the biodiversity it holds. The main types of agroforestry systems in Asturias with an in-depth study of two representative examples, one from a lowland coastal area and the other from the interior mountains, have been revieved. The drivers responsible for changes in the systems and the landscape over time, the role of livestock grazing in landscape conservation and the environmental implications, have been summarized. The coastal areas evolved because of their inability to adapt to new productive models. Numerous small farmers with mixed production systems (meat, milk and various crops) feared conversion to dairy during the industrialization era in the 1960s driven by demand for milk from the cities. This specialization forced an increase in grassland areas at the expense of woodlands and croplands in favourable areas. After the entry in the EU in the 1980s, the territories could not respond to the new productive models. More than 60% of the households disappeared and the surviving farms were mainly converted to meat production. A parallel human emigration to the cities left the countryside inhab-

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ited by an ageing population. These changes were correlated with the reversion of abandoned fields into shrublands and woodlands. In the mountains, the biggest changes in traditional systems started after the entry in the EU. Thousands of small ruminants associated with transhumance plus local herds disappeared, and cattle and horse herds became dominant. The number of households dropped and emigration caused a population crash in the villages, now inhabited by a few elderly people. At the landscape level, certain patches of vegetation, especially broom scrublands, proliferated by colonizing grasslands and heathlands, while holly woodlands became gradually denser and more closed. In both areas, the socio-economics have profound implications on the landscape. Its progressive simplification can lead to decreases in local biodiversity and increases in environmental risks, such as wildfires and the spread of plant and animal diseases. The current density and population structure are insufficient to maintain the landscape and ecosystem services. Regional and national governments face the challenge of coordinating laws, politics and socio-economic support to these valuable systems with multidisciplinary and landscape-scale strategies.

Keywords Abandonment · Biodiversity · Diet selection · Livestock · Transhumance

1 Introduction

Agroforestry has been defined as a dynamic, ecologically based natural resources management system that, through the integration of trees in agricultural landscapes, diversifies and sustains production for increased social, economic and environmental benefits (Leakey 1996). This system is increasingly considered as a solution to limited available resources and as a response to global sustainable development goals, due to the key role it plays in transforming livelihoods and landscapes (ICRAF 2008) and delivering multiple ecosystem services. In Europe, agroforestry is recognized as a sustainable land management practice by the Intergovernmental Panel on Climate Change (IPCC 2014) and a measure in the rural development programs (European Commission 2013b). Importantly, it has been recently included in the "ecological focus areas" of the Common Agricultural Policy (CAP) (European Commission 2013c) and in the EU Forestry Strategy (European Commission 2013a). Several agroforestry systems are among the most diverse high nature value (HNV)[1] systems in Europe, and they have been classified as traditional agricultural

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[1] According to Olivero et al. (2011), the HNV areas cover 6.991 km^2 in Asturias (66% of the surface). Regarding the land uses, 18% are agrarian, 73% forestry and 9% a combination of these. According to this report, Asturias is the province with the greatest surface of HNV areas in Spain. It indicates that croplands for forage share the territory with pastures for livestock and orchards, although a relevant part of the properties is occupied by woodlands, brownfields and wastelands. The high nature value of the province depends on the diversity of land uses in the mosaics.

landscapes (TAL) for retaining certain "traditional" aspects (Plieninger and Bieling 2013).

Agroforestry provides diverse benefits, including (1) inter alia enhancing biodiversity, (2) climate change adaptation and mitigation, (3) food security and (4) reducing rural poverty by increasing soil fertility and crop yields. It also has potential for providing rural livelihoods and habitats for species outside protected lands, connecting nature reserves and alleviating resource use pressure on conservation areas (Chazdon et al. 2009).

In 2015, forests accounted for 31% of the global land area (FAO 2015). Around 33% of European land is covered by forests according to the latest report regarding the State of Europe's Forests (Forest Europe 2015). The report adds a further 36 million ha to the 215 million ha of forests to account for all European wooded areas, and all these areas are expanding. For the period 1990–2015, the greatest expansion was concentrated in Spain (184,000 ha per year) where an increase of four million ha of forest area had been included in targets for 2032. Although Spanish forest policies place great emphasis on such an increase, the latest report highlights that a similar importance should be given to its proper management to avoid risks of forest degradation due to forest fires, pest and disease, abandonment, etc.

The Atlantic region of Spain provides an opportunity to study the expansion of shrublands and forests, together with its associated risks. This region holds 16% of the forest and other woodland areas of Spain (Rigueiro Rodríguez et al. 2005). It can be considered as an important provider of forest and animal products (milk, meat, etc.), the latter mainly from grazing. Around 50 and 23% of the milk meat produced in Spain, respectively, comes from this Atlantic area (Rigueiro Rodríguez et al. 2005).

The importance of agroforestry systems can be exemplified in Asturias. In this autonomous community, 62 out of the 78 municipalities are considered rural (with less than 150 inhabitants km^{-2}). Most of the surface (72%) is occupied by *monte* (the spatial combination of pastures and woodlands) on steep slopes (over 80% of the territory with slopes above 20%) (Gobierno del Principado de Asturias 2011). The landscape is divided between a narrow, productive coastal land with mild weather suitable for cultivation and a wider interior mountainous area with harder environmental conditions and various degrees of isolation, which increase towards the watershed in the Cantabrian Mountains.

In Asturias, the agroforestry systems retain a strategic role in the territorial organization of rural areas, where natural resources have been managed in mixed systems with croplands and pastures for livestock. These two land uses proliferated because of previous strategies of deforestation and clearance of wide surfaces covered by woodlands.

2 Traditional Agroforestry Systems in Asturias

The agroforestry systems in Asturias can be grouped attending to their governance and management strategies:

Fig. 7.1 Agroforestry systems with meadows and hedgerows in Priesca (Villaviciosa, Asturias). *Eucalyptus* plantations can be observed on the top of the hillside

Fig. 7.2 Photographs of the central part of the Puertos de Agüeria summer pastures in the Biosphere Reserve Las Ubiñas-La Mesa from 1956 (left) and 2016 (right). Agroforestry systems occur as a mosaic of holly woodlands, grasslands, heathlands and broom-dominated shrublands. The comparison of both images shows the proliferation of the broom over time

1. Private smallholders in multifunctional bocage landscapes located in lowland areas (Fig. 7.1). They are linked to annual or permanent production and play a key role as ecological corridors. The traditional products from woodlands with chestnut (*Castanea sativa*) (called *sotos*) and oak (*Quercus* spp.) trees provide forage for livestock as well as fruits, timber, firewood, etc. Within the mosaic of land uses, croplands, woodlands and traditional apple orchards coexist with highly biodiverse grasslands which are either grazed or mown (Rosa García et al. 2014). Livestock grazing was traditionally performed by small multispecies herds consisting of cattle (mostly for dairy production), horses, small ruminants and even pigs. Nowadays, either *Eucalyptus* spp. or *Pinus* spp. plantations have conquered wide surfaces, homogenizing the agroforestry systems in a process known as "fermeture du paysage".
2. Mixed silvopastoral systems on common lands linked to seasonal livestock systems at medium to high altitudes (Fig. 7.2). At medium altitudes production is concentrated in the equinoctial seasons, whereas in the mountains they are limited to the summer season due to the harsh environmental conditions. The

> presence of woodlands provides shelter for livestock, especially in the mountains, where the leaves of pruned trees (ashes, willows or birches) can also be used to supplement grass supply during periods of low herbage availability, especially at the end of the summer. Such supplements are also additional fodder (sometimes even better than herbaceous crops) during drought periods or winter forage shortage (Mosquera-Losada et al. 2004). Multispecies herds with cattle and horses (for meat production) plus small ruminants (sheep and goats) traditionally grazed different areas of the landscape. Nowadays, the animal production systems specialize in just cattle and horses. However, the persistence of common lands is crucial for the maintenance of the region's livestock production: close to 50% of the utilized agrarian area is accounted for by these lands.

The persistence of the agroforestry systems in Asturias is threatened by two forces (with the trends extending to the rest of Europe): the intensification of production in certain areas (frequently the most accessible ones) and the abandonment of the most marginal and mountainous ones. Both trends have different origins linked to socio-economic and even political drivers, but they collectively resulted in the structural disruption which has led to the simplification and standardization of traditional landscapes and the potential loss of many unique landscape values and resources (Antrop 2004; Plieninger et al. 2006). These processes correlate with a reduction in biodiversity in certain areas and the disappearance of the traditional production systems which supported those landscapes.

The impact of intensification of production was focused on private properties where the woodland is perceived as an obstacle to mechanization that requires periodical maintenance. The trees were reduced or even eliminated, with a subsequent simplification of the mosaic in the landscape and a decrease in the potential of those areas as ecological corridors, food resources for wildlife, etc. (Harvey et al. 2005). In the most productive areas, the traditional strategies such as mowing or grazing are being drastically replaced by monocultures of, e.g. maize in response to the recent changes in the CAP. In more marginal areas, the intensification has been focused on monospecific plantations of species with rapid growth rates like *Pinus* spp. and *Eucalyptus* spp.

Abandonment occurs both in the private properties located in areas with handicaps for mechanization (e.g. with steep slopes) and in the common lands (where accessibility is even more difficult and weather conditions are even harder). In both cases it contributes to the proliferation of shrublands and woodlands and a progressive simplification of the landscapes, with adverse consequences for biodiversity (Otero et al. 2015). The proliferation of wide and continuous areas dominated by flammable vegetation decreases the capacity to control wildfires, especially within shrubland areas (Fig. 7.3), with potential adverse effects on biodiversity, soil characteristics, carbon sequestration, etc. The recurrence of fires in certain areas reduces their productive potential and accelerates the abandonment of agrarian activities.

Another consequence of abandonment is the loss of cultural heritage and local knowledge on how to use the natural resources in a sustainable way (Parrota and Agnoletti 2007). Cultural and environmental processes have frequently collectively contributed to the configuration of past and present scenarios in agroforestry systems.

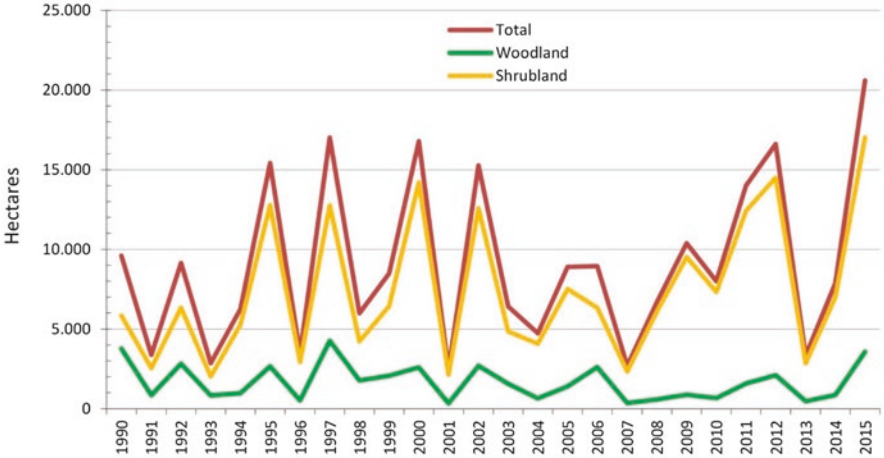

Fig. 7.3 Surface (in hectares) burnt in woodland and shrubland areas in Asturias between the years 1990 and 2015 (Source: SADEI)

This overview of the main agroforestry systems in Asturias reveals that they are dynamic and very complex systems with multiple environmental, socio-economic and cultural implications, and their maintenance is crucial for a sustainable rural development. The Program of Rural Development for Asturias for the period 2014–2020 includes a specific funding strategy for agroforestry systems, but it is still insufficient considering its importance in the territory.[2]

Sustainable management in agroforestry systems requires the integration of tools and strategies within a hierarchical and pluralistic framework of landscape ecology (Naveh and Lieberman 1994). The concept of landscape encompasses more than an area of land with a certain use, shape or function. It is a synthetic and integrating concept that refers both to a material-physical reality, originating from a continuous dynamic interaction between natural processes and human activity (Bertrand 1968), and to the immaterial existential values and symbols of which the landscape is the signifier (Council of Europe 2000). So, the interaction between nature and culture is an essential characteristic of landscapes and forms an important property of sustainability in traditional agricultural landscapes (Antrop 2004). Due to its inherent dynamism, to assess the current conditions of the landscape, historical process must also be known. Depending on the natural and cultural influences in the different periods, the relationships between ecosystems might be changed, and the changes are seen over time in the landscape structure. As a result of the study of the changes, functions and conditions in the mosaic of different sized and shaped patches can be revealed (Wu and Hobbs 2002). Parallel evolution of local populations and infrastructures might also occur.

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[2] https://www.asturias.es/Asturias/descargas/PDF_TEMAS/Europa/FEADER_2014_2020/PDR2.pdf

In this paper analysis has been done regarding changes in the management of the natural resources in Asturias and their consequences in the landscape (from its physical structure to its socio-economic and cultural characteristics). Modifications within a land cover category may be as important for ecological functions, production potential and symbolic value of landscapes as land cover conversion itself. Therefore, there is a need to complement studies of landscape change through more local forms of analysis to calibrate the explanatory power of land use and land cover change at other spatial scales. Two study areas have been analysed, which are good examples of the already mentioned agroforestry systems linked to livestock grazing in either mountain and public lands versus lowland private areas. In both locations, various types of habitats coexist, ranging from sparse forest to coppices of trees and scrub, in a mosaic with patches of open grassland. It has been analysed how land has been managed over time, how rural population and livestock management systems evolved and how these changes are related to the evolution of the main components of the landscape.

3 Materials and Methods

3.1 Study Sites

3.1.1 Puertos de Agüeria

This site covers 450 ha between the municipalities of Lena and Quirós in the Biosphere Reserve Las Ubiñas-La Mesa (Fig. 7.4) and is a protected area in the heart of the Cantabrian Range. The altitudes in the study area range between 1350

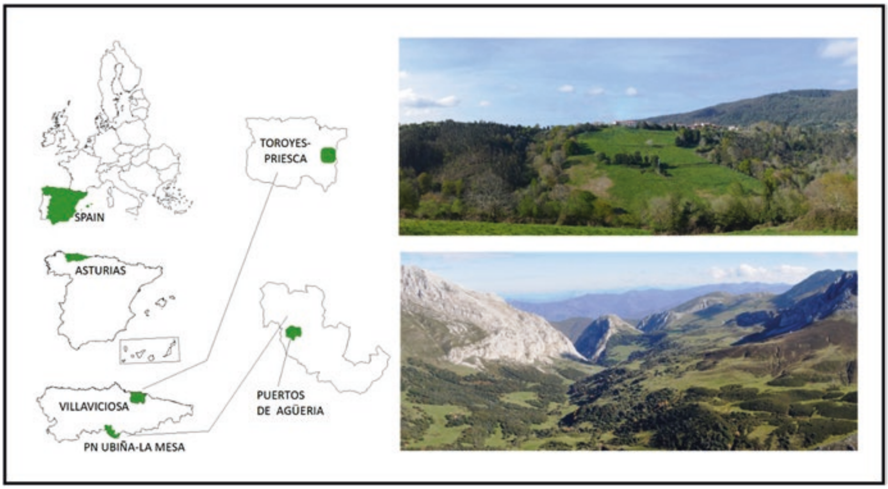

Fig. 7.4 Location of the two study areas

and 1800 m a.s.l. and the slopes between 0 and 78%. The main plant communities are grasslands dominated by *Festuca rubra*, *Agrostis capillaris* and *Nardus stricta*; dwarf heathlands with heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtillus*); scrub with brooms (*Genista florida*); and forests dominated by holly (*Ilex aquifolium*). The spatial combination of these communities generates a heterogeneous mosaic.

The area has been used since the Neolithic as summer pastures for extensive mixed flocks managed by local communities together with transhumance flocks of small ruminants. Tourism is gaining importance but agricultural is still the primary sector (and based on livestock rearing). This area is a good example of mixed silvopastoral systems on common land.

3.1.2 Toroyes-Priesca

This site covers 200 ha around the villages of Priesca and Toroyes. The villages are around 5 km from the coastal line in the council of Villaviciosa (Fig. 7.4). The altitude ranges between 25 and 258 m a.s.l. and slopes from 0 to 60% (mean 21%). The main plant communities nowadays are meadows and woodlands dominated by chestnut (*Castanea sativa*) and several oak species (*Quercus robur*, *Quercus ilex*), as well as *Eucalyptus* plantations and apple orchards (*Malus domestica*). The spatial combination of these communities generates a multifunctional bocage landscape typical of private holdings within lowland area. The local economy is still based on livestock although many houses are only used during weekends/holidays.

In each study area, several locations were established for repeated data recording to track the evolution of the agroforestry systems. The analysis of both study areas followed the same protocol and was based on the following data sources.

3.2 Socio-economic Evaluation

The statistics of population census and structure as well as economic activities were gathered from either local or regional official databases for the last 60 years. The current situation regarding infrastructures (houses and auxiliary buildings) was characterized, and its connection with socio-economic parameters is discussed. To analyse the evolution of livestock management, the number of heads of each livestock species was gathered from local or regional documents. The diet selection and grazing behaviour of each species is discussed due to its implications for changes in vegetation cover. Personal interviews with locals, especially the oldest ones, supported interpretation of the official data for a better understanding of how natural resources were managed.

3.3 Landscape Dynamics

The surface covered by the main types of vegetation was quantified for two periods (years 1956 and 2011). The analysis of aerial photography provided the database for the study of the quantitative and qualitative evolution of the landscape (Fernández García 2004). The aerial photographs from the years 1956 and 2011 were scanned and orthorectified using Agisoft PhotoScan y ArcGIS 10.1. Their photointerpretation was carried out by digitalizing vegetation patches with the module ArcMap 10.1. The first year was selected because it reflects the preindustrial landscapes, and the second one because it reflects recent dynamics. Both cartographic documents and synthetic numerical results were generated. The results were validated via field work and the study of old photographs from those landscapes.

4 Results and Discussion

In the two study areas, profound socio-economic changes in population demography and structure, as well as in cultural heritage, occurred. These dynamics influenced livestock census figures differently depending on the species and productive purposes. The different types of vegetation communities evolved differently depending on several factors. All these changes have had profound implications in the evolution and structure of the agroforestry landscapes and their biodiverse mosaics, with important environmental implications for the current and future scenarios.

4.1 Case Study 1: Mountainous Area in Puertos de Agüeria

4.1.1 Socio-economic Evaluation

A contemporary rural exodus took place around the 1950s. The exodus was selective as mostly women and young men emigrated to the cities, while low-qualified workers and a residual population stayed in the study areas. Between 1950 and 2016, population density dropped. A reduction of 80% in the number of citizens correlated with the rural exodus to the biggest cities in the region (Rodríguez Gutiérrez 1989). The migratory process left a residual population with densities of around 3 inhabitants km^{-2}, which is characteristic of demographic deserts. It also generated an inverted and sex-biased pyramid, sex ratio[3]: 131.9 (Fig. 7.5). The rest

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[3] Relationship between the number of males and females. The equilibrium corresponds to 100; higher numbers indicate more males over females.

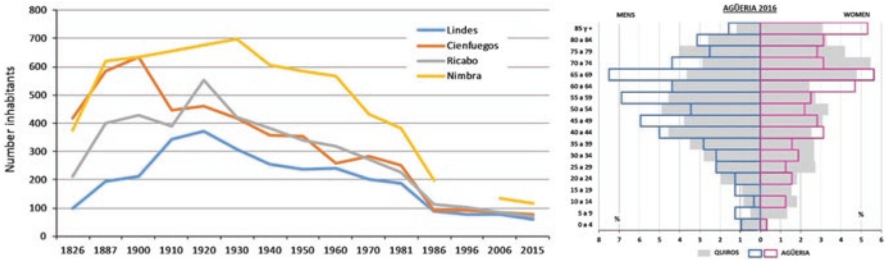

Fig. 7.5 Evolution of the population in the parishes linked to the study area (left) and demographic pyramid for the year 2016 (right)

of demographic indicators characterize a deeply aged population: ageing index,[4] 9.6; dependency ratio,[5] 0.8; and replacement index,[6] 0.2.

These parameters characterize a population unable to face the challenges of maintaining the landscapes and the silvopastoral activity due to impoverishment in quantity (number of individuals) and quality (ageing). Population decrease was correlated with a reduction of households (62% disappeared, Fig. 7.5), and, nowadays, the average age of owners is 58 years old. Given such scenarios, it is evident that new sociopolitical strategies must confront the problem of depopulation and ageing in the rural areas if traditional landscapes are to be conserved.

To define new strategies for the future, we must look to past management of areas under ancient anthropic influence. The Neolithic burial mounds around the study area provide evidence of presence that human groups have managed livestock in the mountains ever since that period (González Collado 2009). The seasonal use of the nutritive mountain pastures by transhumance herds coming from distant areas was consolidated in Spain in 1273 with the creation of the Council of the Mesta by Alfonso X. The later Cadastre of the Marqués de la Ensenada indicates that at least from 1752 the pastures in Agüeria were seasonally grazed by multispecies herds from local communities and transhumance flocks with small ruminants coming from other areas. Transhumance flocks from the Royal Monastery of San Lorenzo del Escorial (Madrid) travelled around 500 km to graze the rented pastures in the study area. Later, shepherds from closer villages rented the area until the year 1985. The last ones came from Villargusán (León). They provided key information about how they managed their flocks in the study area during the interviews.

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[4] Ratio of the population aged 65 years and under 15, with reference threshold 0.5; higher values indicate an ageing population.

[5] Ratio of the population of working age (15–64 years) and population not of working age with threshold 0.5. Higher values indicate dependence.

[6] The replacement index relates the younger working population (15–39 years) with the older (40–64 years). It detects if the positions of the adults will be occupied when they become inactive. The situation is favourable when the index is higher than 1.

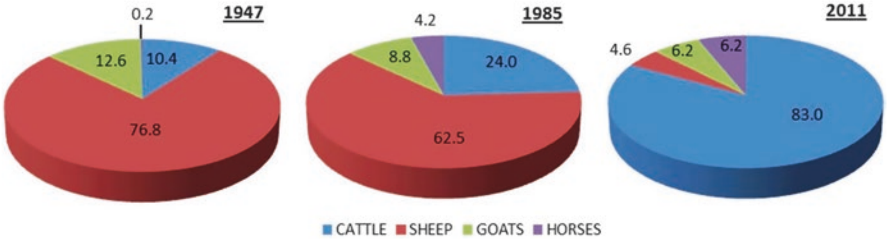

Fig. 7.6 Percentage of livestock types accounting for total census data from 1947 to 2011 in Puertos de Agüeria mountain pastures. Data sources: historical archives of the Government of Asturias and SADEI

Sheep grazing dominated during the 1950s due to the inputs from transhumance, which result in an average of 1750 head of Merino sheep and 250 head of goats being brought to the study area (at least from 1752 to 1985). In 1947 sheep accounted for 76.8% of total grazers on the summer pastures, goats 12.6%, cattle 10.4% and horses 0.2%. In 1985 the dominance of small ruminants was still evident, with 62.5% of grazers sheep and 8.8% goats. Cattle and horse numbers had started to rise, to 24.5% and 4.2% of grazers, respectively, reflecting the farmers' adaptation to reduced labour after the rural exodus began. After the mid-1980s, small ruminants became less abundant (transhumant herds disappeared and the local herds dropped), while larger domestic herbivores (autochthonous beef cattle breeds) flourished (Fig. 7.6). In 2011, cattle already accounted for 83% of grazers, followed by horses (6.2%), goats (6.2%) and sheep (4.6%). However, the actual number of horses may have been higher because the registration of this species was not compulsory. The reduction in census figures for small ruminant is largely a consequence of the discriminatory policy of CAP subsidies (more disadvantageous than for cattle), the readaptation of the farms and frequent conflicts with wild carnivores. Increases in the population of wolves through management plans imposed higher risks for small ruminants, which then require more infrastructure and supervision.

No previous studies have confronted simultaneously the cultural or the environmental implications of the disappearance of thousands of head of small ruminants in the Cantabrian Mountains. For Olea and Mateo-Tomás (2009), this was necessary to assess the ecological impact of the ongoing loss of transhumant activity in these mountains, and the findings should be considered by the new CAP. Having detected the importance of the transhumance of small ruminants in the study area, similar surveys should be performed in the numerous environmentally relevant areas (including a national park) across Asturias to improve their conservation strategies.

The reduction in the number of households and changes in livestock parameters were linked to changes in the use of natural resources. The traditional use changed from extensive silvopastoral systems with shepherded multispecies flocks, which used seasonal auxiliary buildings, to a new system with free-ranging cattle and

Table 7.1 Management strategies in Puertos de Agüeria between 1956 and 2015 and percentage of change in the surface of the main plant communities and number of pastoral buildings between those periods

	In the 1950s	2015	Change (%)
Holly woodlands	Equinoctial pruning	Browsed by cattle at the end of the summer	+ 12.1%
	Browsed by small ruminants		
	Browsed by cattle at the end of the summer		
Shrublands	Guided browsing by small ruminants	Browsed by cattle	+ 47.1%
	Browsed by cattle		
	Cutting and harvesting		
	Burning		
Grasslands	Sequential grazing of local herds: cattle→ sheep→ goats	Free-ranging cattle and horses. Simultaneous competitive grazing	−19.2%
Buildings	Used by locals and transhumance shepherds	Recreational use of surviving ones, disconnected from agrarian activities	−83.0%
	Temporal habitat of the shepherd (May–November)		

horses. The shepherds nowadays do not use the buildings, neither for them nor for the livestock; they visit their flocks every few days. This new strategy results in a less uniform use of the resources compared to the previous systems where most of the different habitats were utilized. The flocks of small ruminants were guided by local shepherds in daily routes across the areas with steeper slopes, whereas cattle and horses reached the mountains in a gradual trip, allowing the use of the mid-mountain pastures situated between the villages and the summer pastures (González Collado 2009). By the end of the summer, the local flocks abandoned the pastures, and the transhumance flocks could expand across the whole area. With this expansion, the sheep and goats spread their dung (fertilizing the area) and browsed the shrublands (full of seeds at that time). Nowadays the animals reach their summer pastures in a single day, no buildings are used and transhumance is gone. These changes correlate with drastic changes in the biological landscape (expansion of certain types of vegetation and decline of others) and in the cultural landscape (the cultural imprint is erased and the associated built heritage collapsed). Lasanta Martínez (2002) described a similar panorama in the central Pyrenees. Table 7.1 includes a summary of the main strategies for the different types of vegetation in each period according to references and information provided by shepherds during the interviews.

The changes in the management of the natural resources concurred with changes in the management of livestock which have had profound implications for landscape dynamics (Fig. 7.7). The nexus between management and landscape lies in the differential diet selection and grazing behaviour of the different herbivore species. These aspects have been rarely analysed simultaneously and even more rarely have been perceived by society as interrelated factors.

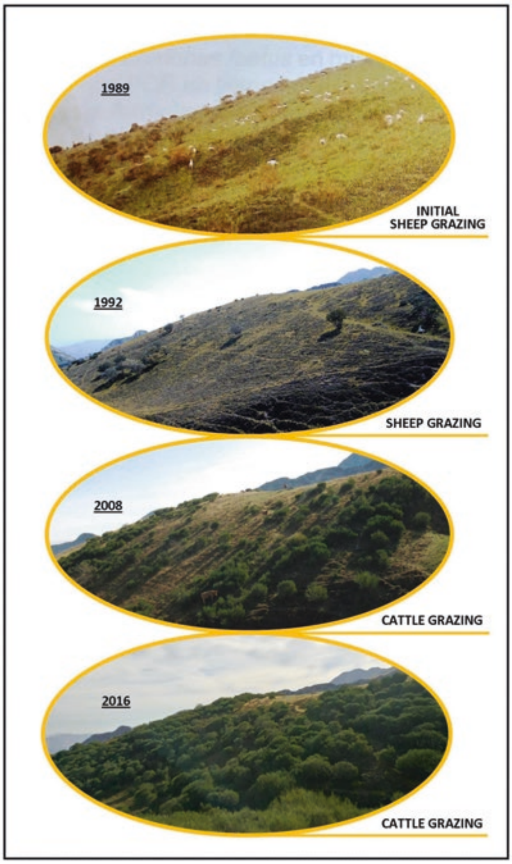

Fig. 7.7 Example of the encroachment of broom (*Genista florida*) scrublands in an area grazed by sheep during the early 1950s and later (after 1995) by cattle in Puertos de Agüeria

Livestock numbers and species lead to different dynamics depending on the vegetation community. Cattle and horses are grazers with preference for grasslands (Ferreira et al. 2013) and do not favour the areas with steep slopes. They both reject broom, probably due to their toxic compounds (Bisby et al. 1994), and browse on heather or holly when the availability of grasses decreases at the end of grazing season in late summer. Although sheep are predominantly grazers, they are also able to utilize heather at a higher degree than cattle (Grant et al. 1987; Osoro et al. 2000a, b; Fraser et al. 2009), whereas goats are browsers with a higher preference for shrubs and steeper slopes (Osoro et al. 2013). They both consume broom and holly, but sheep show a higher preference for grasslands than goats (Rosa García et al. 2012, 2013).

4.1.2 Landscape Dynamics in Mountain Agroforestry Systems

The mosaic of patches of different types of vegetation within the mountain agroforestry system changed over time. A progressive homogenization is observed as result of the proliferation of certain plant communities. These processes did not evolve at

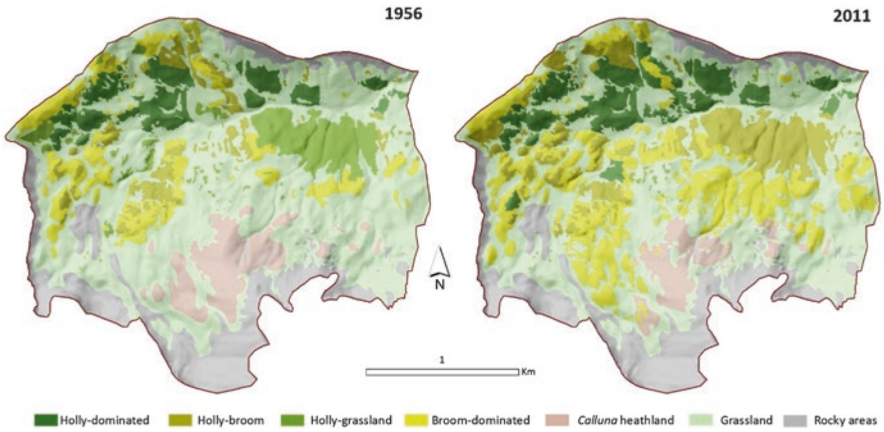

Fig. 7.8 Changes in vegetation cover from 1956 to 2011 in Puertos de Agüeria

Table 7.2 Change in the surface area and associated percentage covered by the main classes of vegetation between the years 1956 and 2011 in Puertos de Agüeria

	1956		2011	
Classes	Surface (ha)	%	Surface (ha)	%
Holly-dominated	29.0	7.5	40.5	10.5
Holly-broom	23.8	6.2	52.6	13.7
Holly-grassland	32.0	8.3	1.3	0.4
Broom-dominated	40.3	10.5	86.0	22.4
Calluna heathland	31.3	8.1	20.6	5.4
Grassland	228.5	59.4	183.9	47.8

a constant speed. The landscape was stable between 1956 and 1985, possibly due to the relative stability of the grazing management strategies during a relatively stable political period. Drastic changes then occurred after 1985 once Spain entered the EU. Around that time transhumance flocks gave up renting part of the study area, and local flocks became dominated by cattle and horses.

The landscape is composed of various plant communities which have the followed specific dynamics. Holly forests have been the main arboreal component in the area. They are a transition series generated after deforestation of those dominated by *Fagus* spp. or *Quercus* spp. Due to their environmental value, they are included in the Habitats Directive, as well as other relevant species such as yew (*Taxus baccata*), which finds in these forests optimal conditions for its survival. These holly forests are also among the biggest and best preserved in Asturias (García 2006). They covered 22% of the total area in 1956 and expanded to 25% by 2011 (Fig. 7.8 and Table 7.2). However, the greatest changes were related to their internal structure (Fig. 7.9), with less open areas found within the patches.

The local shepherds used this holly vegetation as fodder for livestock or materials for the buildings at the end of the summer (traditionally after the moon waned

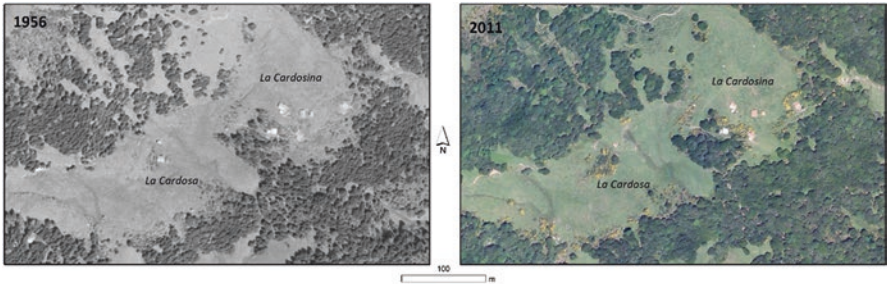

Fig. 7.9 Orthorectified images from 1956 (left) and 2011 (right) showing the increasing density of holly forests around the pastures of the areas called La Cardosa and La Cardosina in Puertos de Agüeria

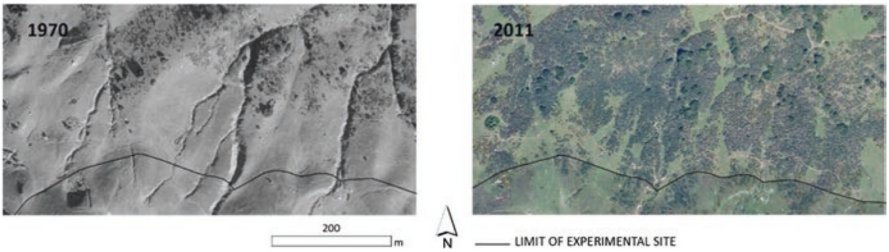

Fig. 7.10 Orthorectified image from 1970 (left) and orthophoto map from 2011 (right) showing the expansion of broom-dominated areas into the grasslands in the study area. The line in the images corresponds to the fences of the SERIDA experimental station

in September). This strategy ended in the late 1980s when the last permit was requested from the local authorities, according to interview respondents and data available in the city hall of Quirós (Table 7.1). Future studies should clarify the environmental implications of these internal changes in the patches of these forests. Nowadays, regional plans for the conservation of holly include the possibility of adapting the strategies to ensure their conservation. The traditional and extensive use of these forests contributed to their rejuvenation and the control of pests (Oria de Rueda 1992).

The shrublands dominated by broom are the communities that have expanded the most. They doubled their surface area from 10.5% in 1956 to 22.3% in 2011 by occupying the grasslands and the open surfaces within the holly patches (Figs. 7.8 and 7.10 and Table 7.2). They expanded in areas with the steepest slopes disfavoured by cattle and horses and which were traditionally grazed by the local flocks of small ruminants in daily itineraries until the 1980s (Fig. 7.7). Broom plants were also browsed in the rest of the areas at the end of the summer when transhumance flocks were allowed to move across the whole summer pastures outside their rented area. These changes in the management and livestock species correlate with the proliferation of the broom.

The evolution of dwarf heathlands was very different. They decreased slightly from 8.1 to 5.4%, primarily due to broom invasion. The heathlands are dominated by heather and bilberry and are listed in Annex I of the EU Habitats Directive 92/43/EEC. Heathlands, in spite of their low nutritive value, might have been beneficial in some respects for the small ruminants that traditionally grazed on these communities. It has been demonstrated that consumption of heather (*Erica* spp. and *Calluna vulgaris*), which can contain substantial concentrations of condensed tannins, can reduce the incidence of parasitic infections by gastrointestinal nematodes in goats (Osoro et al. 2007; Moreno-Gonzalo et al. 2012). Thus, it could play an important role in safeguarding animal health in the mountains. Heathlands are also a key resource for chamois (*Rupicapra pyrenaica*) during winter time (Pérez-Barbería et al. 2010), as well as the endangered Cantabrian brown bears (*Ursus arctos*) and capercaillies (*Tetrao urogallus cantabricus*) which actively feed on plants such as bilberries (Rodríguez et al. 2007; Bañuelos et al. 2008; San Miguel et al. 2012).

The herbaceous-dominated areas have also undergone associated changes which may compromise their potential to deliver certain key services. For example, grasslands play a crucial role in maintaining livestock production systems, but they are also key for the survival of endangered species such as the Cantabrian brown bear, which eats up to 90 herbaceous species, representing up to 80% of its diet during spring (Palomero et al. 2007; San Miguel et al. 2012). The surface of grasslands covered 59.4% in the 1950s, but this had decreased to 47.8% by 2011 (Fig. 7.8 and Table 7.2). In around 30 years, the landscape evolved from a matrix of grasslands with scattered and sparse patches of holly and brooms towards a more compact scenario where the matrix of grasslands has been partly replaced by dense patches of holly and brooms (Fig. 7.10). These changes may be explained by the variations of livestock (with different grazing behaviour) and management strategies used in this period. The density of the larger grazer species increased, whereas small ruminants, which actively browse on shrubs, almost disappeared. In addition, shepherds do not accompany their flocks anymore. Nowadays, animals move freely around a given area, and they are monitored by the owner once a week. This differential management of the flock (Table 7.1) explains the proliferation of certain types of vegetation in areas which were previously grazed more intensively in the guided routes.

4.1.3 Changes in the Cultural Landscape

The disappearance of people and changes in the management of the natural resources have other consequences beyond the biological ones, as it also affects the cultural landscape. The mountain agroforestry systems are linked to important cultural infrastructures necessary for its sustainable use, such as the auxiliary buildings (huts, stables, folds) and trails. The infrastructures have collapsed as shepherds gave up spending the summer periods together with their flocks (Fig. 7.11). Only 13 out of the 76 buildings which were used in the 1950s remain in good condition today (although now used for recreational purposes), 57 are ruins and the remainder are in poor condition (Table 7.1).

Fig. 7.11 Photos of the buildings in the area called El Llano la Sinxeal from 1960 (left) and 2015 (right) in Puertos de Agüeria revealing that all the infrastructures are in ruins

4.2 Case Study 2: The Lowlands of Toroyes-Priesca

4.2.1 Socio-economic Evaluation

The change in population density in this study area across the last 60 years is a good example of the depopulation process that has occurred in the rural areas of Asturias: around 67% of the population was lost between 1956 and 2011 (Fig. 7.12). There is a double loss: in quantity (number of citizens) and in future prospects, as young people (less than 15 years old) now represent less than 10% of the total population. In contrast, the group aged 15–64 years dominate (62%), together with the elderly (more than 65 years), who now represent 30% of the population (Fig. 7.12). The loss of population is linked to the rural exodus to larger cities such as Gijón or Oviedo. These movements generate an inverted pyramid which misses a relevant part of the youngest age groups and produce demographic indexes which are characteristic of a highly aged population: ageing index, 3.1; rate of dependency, 0.6; and index of replacement, 0.5. All these values reveal that the low generational replacement is handicapped as well as prospects to maintain the rural activities and the traditional landscapes based on agroforestry systems which require active management for their conservation. In fact, the consequences of the loss of the traditional ecological knowledge which used to be transferred from the oldest to the youngest generations have been rarely taken into consideration, and it may play a key role in the sustainable use of the natural resources.

The main traditional activity was small-scale livestock management until 1940. It was focused on mixed systems (milk and meat) with cattle, complemented with a subsistence agriculture carried out on small properties. The contemporary process of industrialization, and the consequent demand for fresh milk from the cities, led to the “milk temptation” (Ortega Valcarcel 1989). As a response, traditional farms, which were adjusted to the local conditions, were converted into more specialized dairy systems (Fig. 7.13) that required drastic changes: (a) the substitution of the dual-purpose livestock native breeds by more productive exotic ones (firstly Blue Mountain and later mostly Holstein) and (b) the disappearance of wide areas of crops, which were converted into pastures for fodder production.

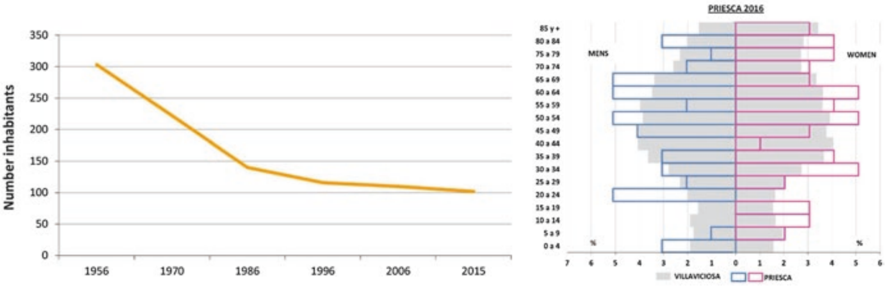

Fig. 7.12 Demographic evolution in the parish of Priesca between 1956 and 2016 (left) and population pyramid in 2016 (right)

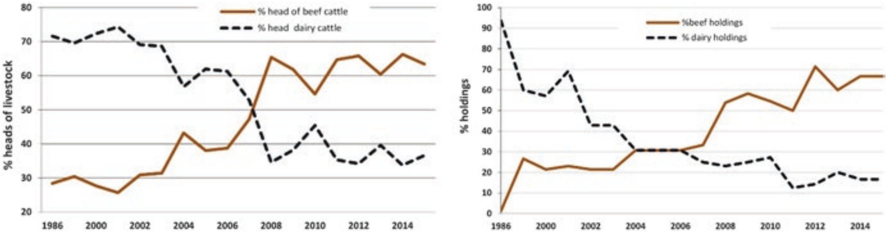

Fig. 7.13 Changes in the number of head of livestock (left) and in the number of holdings (right) aimed at livestock production according to their productive purposes (meat or milk)

The poor alignment of this new production model to the characteristics of the marginal territories (with steep slopes, deficient communications, the dominance of smallholdings with small properties in profusely parcelled areas, etc.) involved a dramatic drop in the number of households (60% disappeared) and the subsequent conversion of the survivors to meat production systems. Whereas 94% of the households were dairy farms in 1986, only 16% persist nowadays. These changes led to the reintroduction of traditional autochthonous beef cattle breeds.

The current average age of the farmers is 55 years old, and this fact jeopardizes as much as any other one the persistence of farming activities in these rural areas. One symptom of this decadency (inability to adjust to the new system and contemporaneous emigration) is the proliferation of forest plantations to provide an extra income with minimum management requirements for owners already living in other areas.

The demographic and socio-economic changes have had implications in the landscape, linked to the loss of traditional strategies, which used to be developed in the mosaic of land uses that generated the traditional bocages of high environmental value (Gil-Tena et al. 2015).

4.2.2 Landscape Dynamics in Coastal Agroforestry Systems

The greatest changes in the landscape are associated with the expansion of the woodlands (Fig. 7.14) in areas with productive handicaps, with steeper slopes or with difficult access, where plantations of *Eucalyptus globulus* have proliferated (Table 7.3 and Fig. 7.15).

This change is associated with the rural exodus and the maintenance of properties under expectant capital gain, as revealed during the interviews. Plantations provide an extra income in areas that became unused once the owners or their descendants gave up farming. These plantations with exotic species have less biodiversity (both flora and fauna) than the autochthonous forests (Gardner et al. 2008) and can have negative effects on soils, water flows (Poore and Fries 1995) and other ecosystems in the nearby areas (Rosa García et al. 2014).

Native woodlands have also expanded (17%, Table 7.3) and their internal structure changed (Fig. 7.14). Eucalyptus trees have occupied the interspersed open areas in certain woodlands covered with chestnut and oak trees. Timber used to be an important income for the local economies and was used for several purposes (for heating, building, etc.), but it progressively lost its importance. These changes are correlated with the increase of the vegetation density within the woodlands which were not cleared anymore (Fig. 7.15). This lack of management leads to landscape homogenization. The lack of woodland breaks increases the risk of larger fires as it is currently happening in many areas across northern Spain. This continual forest cover and management have also contributed to the expansion of serious diseases such as chestnut blight (*Cryphonectria parasitica*) (Conedera et al. 2004; González Varela and González Fernández 2006).

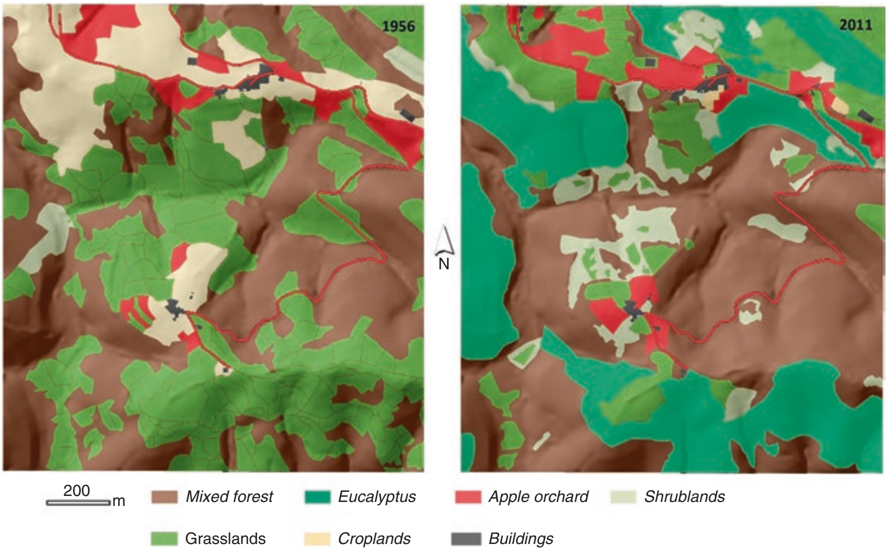

Fig. 7.14 Changes in vegetation cover from 1956 to 2011 in Toroyes-Priesca

Table 7.3 Evolution of the surface covered by the main classes of vegetation between the years 1956 and 2011 around Toroyes-Priesca

	1956		2011	
Classes	Surface (ha)	%	Surface (ha)	%
Native woodlands	73.9	37.0	86.6	43.4
Eucalyptus plantations	2.3	1.2	57.9	29.0
Apple orchards	8.0	4.0	9.8	4.9
Shrublands	2.7	1.4	15.9	8.0
Grasslands	84.5	42.4	27.4	13.8
Croplands	26.8	13.5	0.5	0.2
Buildings	1.3	0.7	1.3	0.7

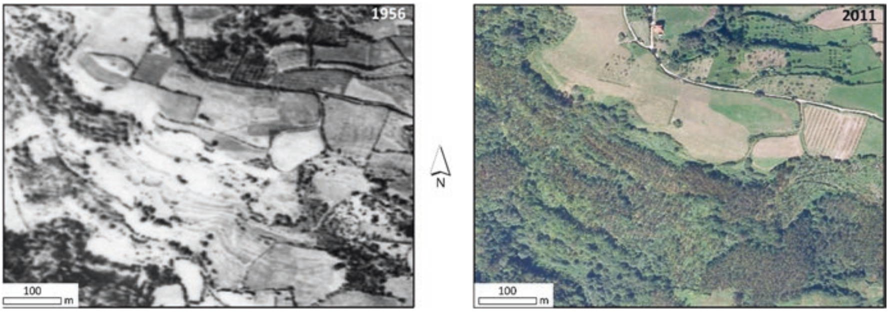

Fig. 7.15 Orthoimages from 1956 (left) and 2011 (right) showing an example of the expansion of trees (mostly *Eucalyptus globulus*) in previous meadows and native forests around Toroyes. In the image from 1956, the open areas between the trees can be observed, whereas the same area is more densely vegetated in 2011

The increase in the agroforestry areas (24%), mostly apple orchards, is related to a higher demand for apples for cider production. Mostly of this activity was historically for local supply, but recently it has gained importance in the local economy. The new plantations have a different internal structure to maximize production. The traditional orchards had densities of around 205 trees ha^{-1} following a quincunx frame, with the biodiverse meadows behind the trees grazed by livestock and/or cut for forage (Fig. 7.16). The new plantations have higher densities (500–1450 trees ha^{-1}) in a regular organization in rows, a higher water demand, and they are not used for livestock.

The areas covered by shrublands increased by 90% (Fig. 7.14). The proliferation of woody vegetation was linked to the changes in the production model from dairy to meat production, leading to grasslands losing their role as fodder providers and hay cuts no longer being performed. Many grasslands, especially in the isolated and steepest slopes, have been progressively invaded, initially by bracken (*Pteridium aquilinum*) and subsequently by gorse (*Ulex europaeus*) and brambles (*Rubus* spp.) (Fig. 7.17). These shrublands increase fire risk, including in areas close to population centres (Fig. 7.18).

Fig. 7.16 Traditional apple orchards with distant trees in Toroyes (left) versus young modern plantation with the trees in rows in Priesca (right)

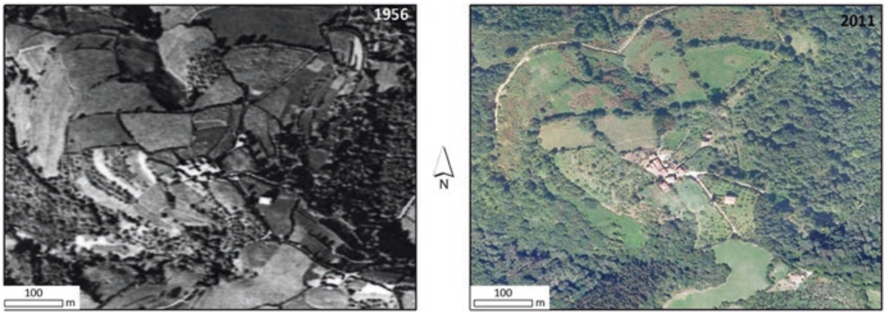

Fig. 7.17 Orthoimages from 1956 (left) and 2011 (right) showing the expansion of shrublands on previous croplands and grasslands, as well as the thickening of the hedgerows around Toroyes

Fig. 7.18 Grasslands invaded by bracken (left) and croplands colonized by gorse and brambles (right) around the houses of Toroyes

Another dramatic change is related to the disappearance of croplands, key in the subsistence local economy in the 1950s. They were reduced by around 98% as a response to the "milk temptation" during the period 1960–1986 and the subsequent conversion into grasslands (Ortega Valcarcel 1989). Later, as farms were redirected towards meat production, when population densities in the area were already lower, grassland management became imprecise and oriented towards grazing and silage rather than hay cutting or mixed systems. These changes have led to the loss of around 68% of the grassland area, with the remaining grasslands was managed very differently.

The grasslands and the hedgerows surrounding them required periodic management for their conservation. This was not considered in the new production model, forcing the holdings to increase the number of animals when families were becoming smaller due to the exodus. So, key management activities such as equinoctial grazing, summer hay cutting, pruning of the hedges, weeds' removal, etc. mostly disappeared, and a less demanding strategy of simple all-year-round grazing is now deployed. By contrast, mixed management strategies such as hay cut and livestock grazing contribute to the preservation of flora and fauna biodiversity (Rosa García and Fraser 2014), even within apple orchards (Rosa García and Miñarro 2014). In addition, the unmanaged hedgerows have evolved into narrow linear woodlands (Fig. 7.17).

5 Conclusions

Agroforestry systems evolve continuously, reflecting social and economic changes of a society at a given time. History not only records gradual changes in the landscape but also many sudden transformations caused by natural disturbance and human action (Antrop 2008). In this work, periods of stability were deducted in the landscape interrupted by rapid changes associated with sociopolitical events, highlighting the interconnection between the environment and the human-induced processes that take place even at a greater scale (i.e. entry in the EU).

Nowadays, landscape is acknowledged as performing many functions and delivering a range of services. Its future has, and will, depend upon developing new functions that have economic significance. Tourism and recreation are often suggested as viable alternatives to primary production, but a paradox is also observed as the associated development they bring often means the destruction of the original qualities (Vos and Klijn 2000). Coastal and mountain areas, which have important ecological values, are the most affected. The traditional activities are not replaced by new ones. Instead it can lead to a profound simplification of the traditional agroforestry systems and associated landscapes which attract that tourism.

The loss of natural wealth is obvious here, but changes in the socio-economic and cultural elements are not so obvious, although they are vital for the maintenance of past and future landscapes. In both study areas, the current population densities and age structures (mostly elderly) cannot maintain the activities which are supposed to preserve the landscape in all its perspectives. From the cultural perspective, there is a need to acknowledge the role of the rural population in the maintenance of these systems and also their role in preserving the traditional knowledge of the use of natural resources. Most frequently, and especially within protected areas, the importance of preserving the cultural heritage is clearly secondary to the biodiversity, despite the fact they are tightly interconnected.

The coastal areas have responded to the conflict between land use changes and their drivers increasing the area for tourism and recreation, industry or forest plantations, with corresponding changes in the area left for agriculture. The farmers feel incapable of competing, while at the same time changes in EU policy seem to force them to increase their holding size in areas where land is more oriented to other activities. In many cases the consequences of the changes in land use have not been analysed despite their adverse effects for both the local human communities and environments. In present study area, the expansion of eucalypt plantations followed no plan, and its consequences have not been measured yet. *Eucalyptus globulus* is an exotic species that impoverishes soils and biodiversity and increases fire risk and pest expansions (Rosa García et al. 2014). None of the plantations in the study area provides essential income for the rural economy; instead they act as source of additional income for owners that have frequently emigrated.

In the mountains the productive handicaps and its isolation, together with the bureaucracy associated with protected areas, led to a decline in traditional activities This in turn led a rapid transformation of the agroforestry systems, adversely affecting their heterogeneity. The recognition of the active role of traditional activities in the maintenance of such systems and the implementation of adequate agri-environmental schemes (based on scientific knowledge) are fundamental for the preservation of related landscapes.

To summarize, in this document it has been confirmed that Cantabrian agroforestry systems play essential environmental and socio-economic roles; they are multifunctional and provide a wide variety of public goods and services:

1. Food safety and quality food production based on extensive production through the sustainable use of natural resources
2. Fire prevention by arresting the accumulation of flammable shrublands
3. Provision of mosaic landscapes that enhance biodiversity, turning most of them into agricultural systems of high nature value
4. Mitigation of climate change, as they constitute one of the most effective CO_2 capture systems
5. A key territorial basis for small farms based on livestock production
6. Conservation of cultural heritage, both tangible (infrastructures, structural elements, livestock buildings, etc.) and intangible (models of sustainable management of natural resources)

Finally, these agroforestry systems demand integrated strategies for their conservation, delivering:

1. Protection of natural and semi-natural vegetation
2. Revitalization of low-intensity farming systems
3. More incentives and substantial financial support for farming that maintains biological and historical values
4. Encouragement of low-input farming and agroforestry

5. Combining local knowledge and traditions with concepts of landscape ecology to develop "new" cultural landscapes and agro-systems where young generations should have a key role
6. Valorization of the multifunctional role of the systems by urban societies and their co-responsibility in the preservation of the services
7. More research on traditional sustainable agriculture and subsequent application of the findings

By encouraging all these aspects, a demographic revitalization is more likely to occur, and this will be key to maintaining these important agroforestry systems.

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Chapter 8

Agroforestry Systems as Adaptation Measures for Sustainable Livelihoods and Socio-economic Development in the Sikkim Himalaya

Ghanashyam Sharma and Eklabya Sharma

Abstract The Sikkim Himalayan Traditional Farming Systems (TFS) show good examples of how indigenously managed small patches of cultivated production agroecosystems constitute a larger landscape management approach and how contribution of such agriculture by the small-scale marginal land has contributed to ecological, economical and food security while providing employment to over 80% of the population directly or indirectly dependent on them. Mountain food security is mostly dependent on small and marginal TFS which are dynamic and exhibit examples of indigenously managed farm-based, farm forest-based, Alnus-cardamom-based, forest-cardamom-based and Albizia-mixed tree-mandarin-based homegarden agroforestry systems.

Multipurpose tree density was remarkably high (198–284 ha^{-1}) in agroforestry systems and contributes > 200 species of NTFPs which are sold in the weekly hatts (small movable markets) for earning cash. Indigenous soil fertility management through tree-based N fertilization of soil has proved beneficial with alder contributing 95–116 N kg ha^{-1} $year^{-1}$ while Albizia contributing 14–22 kg N ha^{-1} $year^{-1}$. Of the identified livelihood options, employment and remittances contributed 53% to household income, large cardamom contributed 29.20%, generating an average income of US$ 911 $year^{-1}$ $household^{-1}$, followed by livestock, which contributed 12%. The remaining sources of income were other cash crops, beekeeping, off-farm labour and employment under the MGNREGA, which together contributed only 4% of household income. Output to input ratios in the form of cash were clearly the highest in cardamom-based agroforestry and proved to be the most energy efficient and economically viable, as well as the most cost effective, among all agroforestry systems.

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Climate variation in the region has contributed to an unpredictable or erratic rainfall pattern, drying up of local springs and streams, species migration to higher elevations, shift of sowing and harvesting period of crops, emergence of invasive species and incidence of diseases/pests in crops as well as in fodder species. Under such circumstances, promotion of homegarden agroforestry systems through community innovations and investments would be a successive strategy for adaptation, mitigation and livelihood security. At the wake of climate scenarios and the pressure of globalization, revitalization of small and marginal farms and production agroecosystems, which emphasizes diversity, synergy, recycling and integration, and social processes that value community participation and empowerment, proves to be perhaps one of the only viable options to meet present and future food needs and adaptation to climate change. The "Organic Mission" of the Government of Sikkim is expected to enhance farmers' livelihood strategies, particularly in areas under high ecological, climatic and economic stresses and risks.

Keywords Traditional farming systems · Homegarden systems and practices · Sikkim Himalaya · Traditional knowledge systems · Organic mission

1 Introduction

In many areas of the developing world, traditional farmers have developed and/or inherited complex farming systems, adapted to the local conditions that have helped them to sustainably manage harsh environments or climatic variation and to meet their subsistence needs, without depending on mechanization, chemical fertilizers, pesticides or other technologies of modern agricultural science (Toledo et al. 1985; Brookfield 2012; Mbow et al. 2013; Pandey et al. 2013; Sharma et al. 2016a). In the world over, agriculture occupies 40% of the land surface, consumes 70% of global water resources and exploited biodiversity at genetic, species and ecosystem level and is an essential component for human wellbeing, and at every point of production, agriculture influences and is influenced by ecosystems, biodiversity, climate and the economy (Altieri and Kooohafkan 2008). The agroecological systems are primarily nourished by the traditional knowledge systems of the communities and are deeply rooted by the rationale of traditional small-scale agriculture, representing long-established examples of successful agricultural systems characterized by a tremendous diversity of domesticated crops and animal species maintained and enhanced by ingenuous soil, water and biodiversity management regimes. Such systems have fed much of the region's population for centuries and continue to feed people in many parts of the planet (Koohafkan and Altieri 2010).

Sikkim Himalayan traditional farming systems (TFS) show a good example of small-scale homegarden agroforestry systems indigenously managed by farmers since ancient times for their socioecological, sociocultural and socio-economic benefits. Homegarden agroforestry systems are designed by growing multipurpose trees, shrubs and a diversity of traditional crops and thus are ecologically sustainable which are believed to be more diverse to provide multiple services for household than other monocropping systems, and this is due to the combination of crops, trees and livestock (Linger 2014; Sharma et al. 2016a). Most of these land use practices are agroforests, open cropped areas and adjacent forests. The main objective of establishing agrarian agroforestry system-based agriculture management in the Sikkim Himalayan region is the rational utilization of land and water resources with reduced damage to the natural resources. However, there are several challenges in transitioning to high production, intensified, resilient, sustainable and low-emission agriculture (FAO 2010).

Sikkim Himalayan TFS is the live example of homegarden agroforestry systems consisting of traditional crop – multipurpose tree – livestock mixed farming and is the basis of livelihood of local communities and backbone of rural economy (Rao and Saxena 1996; FAO 2007; Kumar and Nair 2006; Sharma and Dhakal 2011; Sharma and Rai 2012; Sharma et al. 2016a).

Considering the spatial extent of the TFS landscape, the beautifully designed and well-located patches along the mountain slopes form minor land use diversity in the "matrix of forests" and are highly significant for socioecological and socio-economic considerations (Maikhuri et al. 2001; Sharma 2012). Agriculture is the main source of livelihood for 80% of the population of Sikkim for economic, food and nutritional security and contributes to around 17% of the Gross State Domestic Product (Kumar 2012; Bhutia et al. 2014; SAPCC 2015). The diverse forms of indigenously designed homegarden agroforestry systems such as cardamom-based agroforestry, mandarin-mixed tree-based agroforestry, farm-based agroforestry and forest-based agroforestry are socioecologically suitable, socioculturally accepted and socio-economically remunerative practices paramount for livelihood security of the marginal farmers in the region (Sharma et al. 2009, 2016a, b; Sharma and Dhakal 2011; Sharma and Rai 2012).

While there are emerging threats to the typical homegarden agroforestry systems in the Himalayan region due to the number of development-related factors including climate change, the Himalayan region including the states of Uttaranchal, Sikkim, West Bengal and Arunachal Pradesh in India is under fast developmental shift through hydropower projects, pharmaceuticals and other infrastructure development, all of which have inadvertently impacted on the economy, culture and the environment of the mountain communities (Sharma and Dhakal 2011; Sharma and Rai 2012; Chaudhury 2016; Sharma et al 2016a). Considering the imperatives of mountain specificities which are in larger extent ignored by development interventions will result in resource misuse and subsequent accelerated environmental degradation (Jodha 1989). This situation, if continued, will impact not only the inhabitants of the mountainous region but also the downstream communities. Such negative impacts of unplanned development, insensitive to mountain specificities, are already becoming common, the most frequent being the regular incidences of landslides, river obstructions and flash floods in the mountain and recurrent floods in the plains (Singh 2006).

In this chapter, we review and analyse how diversity of adaptive practices of homegarden agroforestry systems is managed by indigenous communities, the flow of energy and resources including cash, what contributes to household income in an integrated farming system and how this entire process of climate-resilient traditional farming practices is now influenced by organic policy of the Government of Sikkim. On a broader context of discussions on agricultural sustainability, we proposed to discuss sociocultural, socio-economical and socioecological dimensions which are often overlooked in discussion on mainstreaming agricultural sustainability.

2 Agroforestry Diversity in TFS

The TFS in Sikkim are dynamic based on indigenous farming practices (agri-horti-pastoral system, agri-silvopastoral system, horti-silviculture system, agri-horti-silvopastoral system, livestock-based mixed farming, sericulture-based farming), designed and redesigned on a rotational basis according to situation, requirement and time. The agroforestry systems in Sikkim Himalaya in general include homegardens, alley cropping, growing multipurpose trees and shrubs on farmland, boundary planting, farm woodlots, orchards or tree gardens, plantation/crop combinations, shelterbelts, windbreaks, conservation hedges, fodder banks, live fences, trees on pasture, livestock and beekeeping as was described by Nair (1993) and Sinclair (1999).

The traditional agroforestry practices under TFS are broadly categorized into five systems: farm-based, forest-based, *Alnus*-cardamom-based, forest-cardamom-based and *Albizia*-mixed tree-mandarin-based systems (Table 8.1). In farm-based agroforestry, farmers manage multipurpose tree species for fodder, fuel and timber, along with other direct and indirect uses within and around the surrounding open cultivable land (Fig. 8.1). In many instances, trees are planted on terraced risers to increase soil stabilization and intercropped with a variety of other plants used in the

Table 8.1 Different agroforestry systems with their common characteristics

Agri-horti-silvopastoral system	Agri-silvopastoral system	Horti-silviculture system		
Farm-based	Farm-forest-based	*Alnus*-cardamom	Forest-cardamom	*Albizia*-mixed tree-mandarin
Multi-layered vegetation structure with fodder species, shrubs and understorey crop-based garden agroforestry	Multipurpose tree species for fodder, fuel and timber and bamboo groves and animal feed bank and for other productive needs	Large cardamom-based agroforestry with *Alnus nepalensis* as shade tree for understorey cardamom crop	Mix tree species as shade trees for the understorey cardamom crop grown	Multilayer arrangement of fruit orchards predominantly with mandarin orange trees as the main horticultural crop

(continued)

Table 8.1 (continued)

Agri-horti-silvopastoral system	Agri-silvopastoral system	Horti-silviculture system		
Multiple intercropping in terraced productive zones, multipurpose trees and shrubs grown on the terrace edges, agrobiodiversity is high, diversity of paddy grown in terraces and pulses on bounds	Managed as support land for fuel, medicines, fodder, construction materials, NTFPs and other minor forest products, pasture lands, catchments for water sources, etc.	Act as catchments for recharging springs, corridor for mammals, habitat for wildlife, provides fuelwood and ground fodder	Diversity of timber trees and fodder trees are also grown, is catchment for recharging springs, corridor for mammals, habitat for wildlife	Agrobiodiversity rich, fodder trees, multi-cropping of understorey traditional crop varieties, buckwheat, beans, protein crops, yams, taros, etc.
Homesteads involving animal husbandry, traditional beekeeping, vegetable crops, medicinal plants, etc.	Grazing livestock, remunerative to farmers for food and cash	Highly remunerative system in terms of ecological adaptability and economic return	Ground fodder, NTFPs, medicinal plant, soil and water conservation, highly remunerative	Highly remunerative as cash crops such as orange/ginger and tuber/food crops, vegetables are grown
Nutrient-exhaustive, high-input system	Low-input system	Low-input system	Low-input system	Nutrient-exhaustive, high-input system

Fig. 8.1 A farm-based agroforestry system

Fig. 8.2 A farm-forest-based agroforestry system

household economy. This system consists of *Sukha-bari* (rainfed field) with maize-potato, maize-ginger and vegetables and *Pani-khet* (rice-based) with rice followed by winter crops and vegetables. Here, management of fodder trees surrounding vegetable and cereal production is integral to maintaining the livestock.

Farm forest-based agroforestry is a managed support forestland adjacent to the open cropped areas, where farmers grow multipurpose trees on certain parcels consisting of bamboo and multipurpose timber species (Fig. 8.2). Under farm forest-based private agroforestry, farmers do not cultivate food crops; instead they allow non-timber forest produce to grow understorey. In a unit of household landholdings, apart from other land uses, the forest-based agroforestry functions as aquifer recharge catchments. Farm forest-based agroforestry is practiced, growing multipurpose species for timber and fuel wood. Farmers grow bamboo groves and woods for making ploughs and other farming implements and primarily for protecting the open agriculture terraces.

Large cardamom-based agroforestry is categorized into two sub systems: *Alnus*-cardamom and forest-cardamom systems (Figs. 8.3 and 8.4). Large cardamom (*Amomum subulatum*) is a high-value cash crop which, when properly cured, stores well for extended periods. Large cardamom generally produces low volume per plant, but the trade-off is that it requires relatively low labour inputs. Himalayan alder (*Alnus nepalensis*) is a naturally occurring tree associated with cardamom, valued for its ability to provide appropriate shade, fix atmospheric N_2 and generate nutrient-rich litter which helps facilitate a more efficient cycling of nutrients (Sharma et al. 2008, 2010). It is a pioneer species on freshly exposed landslide soils, denuded habitats, rocky and landslide-affected slopes, steep stream banks and natural areas. Farmers then gradually plant cardamom saplings and maintain the tree density on a yearly basis, and thus they establish the *Alnus*-cardamom association (Sharma 2001).

Fig. 8.3 *Alnus*-cardamom-based agroforestry system

Fig. 8.4 Forest tree large cardamom-based agroforestry system

The indigenous farmers have sound understanding that alder trees support soil fertility, and thus they plant or allow *Alnus* to grow naturally in different land use systems. Scientific understanding following adequate analysis of *Alnus*-cardamom agroforestry systems has proven this traditional practice as economically remunerative, ecologically adapted, with comparatively high carbon sequestration potential

Fig. 8.5 Mixed-tree mandarin orange-based agroforestry system

(Sharma et al. 2000, 2002a, b). Sikkim produces about 40% of the world's large cardamom, standing second after Nepal (Partap et al. 2014). This is a traditionally innovated, self-reliant agroforestry system – one which exploits a naturally occurring plant guild in order to take advantage of its variety of ecosystem services while simultaneously meeting a unique market niche (Sharma et al. 2009).

Albizia-mix tree-mandarin is yet another promising agroforestry system at lower elevations (250-1800 m), in which mandarin orange trees are the principal cash crop intercropped with maize, ginger, buckwheat, finger millet, pulses, oilseeds, taro and yam (Fig. 8.5). *Albizia*, another N_2-fixing tree species, is also commonly grown with other trees in this mandarin-based agroforestry system (Sharma 2012). The diversity of crops and associated tree species is maintained in the system for meeting household food, fodder, medicine and other subsistence needs. Farmers consider *Alnus* an excellent shade tree for understorey large cardamom crop and a valuable timber at maturity (30–40-year-old trees), while they consider *Albizia* a plant that primarily enriches soil fertility and also used as fuelwood and timber when the trees are matured with >40 years age (Sharma 2001). As a management practice, farmers cut down matured *Alnus* and *Albizia* trees considering that they no longer support soil fertility (Partap et al. 2014) and utilize the space for growing a variety of pulses and cereals.

3 Stand Dynamics and Adaptation Measures on Agroforestry Practices

Sharma et al. (2016b) have carried out detailed study of the dynamics of agroforestry stand in the Sikkim Himalayan TFS. The tree density was remarkably high in farm-forest-based agroforestry (843 ± 132), 4.26 times that of farm-based, 3.01 times of *Albizia*-mixed tree-mandarin, 2.02 of *Alnus*-cardamom and 1.17 times that of forest-cardamom agroforestry. NPP was comparatively high in the *Alnus*-cardamom systems, nearly 3.60 times that of *Albizia*-mixed tree-mandarin, 2.71 times more than farm-based and 2.45 and 1.49 times that of forest-cardamom and farm-forest-based agroforestry, respectively. Agronomic yields were highest in the *Albizia*-mixed tree-mandarin and farm-based system which included all the crops grown within a year. Cardamom yield ranged between 260 and 310 kg ha^{-1} $year^{-1}$ (Sharma et al. 2016c).

NTFPs from agroforestry present a valuable source for household economies, as well as for augmenting the household diet. A total of 56 species of edible NTFPs are collected from the farm-forest-based agroforestry, while 27 species from forest-cardamom-based, 16 species from farm-based and 9 species from mandarin-based agroforestry systems. Apart from supporting income generation from NTFPs, the agroforestry also supports fodder production for livestock management. Fodder collection from both trees (57 species) and ground fodder (61 species) was highest in farm-forest-based agroforestry, followed by forest-cardamom and then *Albizia*-mix tree-mandarin. A considerably high amount of dry crop residue is collected from the farm-based and *Albizia*-mixed tree-mandarin agroforestry systems, which is traditionally stored to feed the farm animals during the lean season. Crop residue is not collected from the cardamom-based agroforestry intentionally, as it would disrupt the natural nutrient cycle. In the TFS, around 90% of the families have stall-fed animals, while 5% graze in their private land.

Litter residue collected from agroforestry systems is primarily used for livestock bedding, which could be considered a traditional knowledge system (TKS), as it began to generate higher-quality compost for crops. Litter is also used for mulching, especially in ginger, turmeric and yam seed bedding. Both farm-based and farm-forest-based agroforestry contributed high-stand litter production. Extraction of fuelwood for household usage is comparatively higher from the farm-forest-based and farm-based. However, the greatest amount of fuelwood extracted is utilized for curing of cardamom capsules in a traditional kiln, locally called *bhatti* (70–75 kg for drying 100 kg of raw cardamom).

Tree-based N fertilization of soil has proved beneficial in soil fertility maintenance (Table 8.2). The alder species planted as shade trees in cardamom-based agroforestry contribute to as high as 95.25 kg ha^{-1} $year^{-1}$, and the alder trees in farm-forest-based agroforestry contribute to 59 kg ha^{-1} $year^{-1}$. Similarly, *Albizia* planted in farm-based and *Albizia*-mix tree-mandarin agroforestry contribute to 14 and 20 kg ha^{-1} $year^{-1}$. The highest amount of N_2-fixation was recorded in alder-cardamom agroforestry (116 kg ha^{-1} $year^{-1}$). Nitrogen input ranged between 14 and 22 kg ha^{-1} $year^{-1}$ in *Albizia*-mixed tree-mandarin, farm-based and farm-forest-based agroforestry systems (Sharma et al. 2016b).

Table 8.2 Tree density and biological nitrogen fixation by *Alnus nepalensis* and *Albizia* spp. in the agroforestry stands (Sharma et al. 2016b)

Parameters	Farm-based agroforestry	Forest-based agroforestry	*Alnus*-cardamom agroforestry	Forest-cardamom agroforestry	*Albizia*-mixed tree-mandarin agroforestry
Agroecological range 800–1200 m					
Tree density (trees ha^{-1})					
Albizia spp.	40 ± 10	55 ± 20	76 ± 15	46 ± 12	72 ± 10
Alnus nepalensis	26 ± 9	192 ± 26	310 ± 30	–	25 ± 8
Nitrogen addition through fixation (kg ha^{-1} year^{-1})					
Albizia spp.	7.92	10.89	15.73	9.52	13.61
Alnus nepalensis	6.51	48.00	77.52	–	6.25
Total	14.43	58.89	95.25	9.52	19.86
Agroecological range 1200–2100 m					
Tree density (trees ha^{-1})					
Albizia spp.	20 ± 6	32 ± 9	–	28 ± 9	26 ± 8
Alnus nepalensis	43 ± 10	56 ± 10	417 ± 17	–	32 ± 12
Nitrogen addition through fixation (kg ha^{-1} year^{-1})					
Albizia spp.	4.14	6.62	–	6.00	4.91
Alnus nepalensis	12.04	15.68	116.76	–	8.96
Total	16.18	22.30	116.76	6.00	13.87

Values are pooled from three site replicates (±SE)
Average active 11 h of the day and C_2H_2:N_2 ratio of 3:1 were used

4 Nutrient Availability in Agroforestry Stands

Sharma et al. (2016b) have carried out a detailed study on the nutrient availability of agroforestry stands (Table 8.3). Soil texture was classified as sandy loam in non-cardamom-based systems, whereas cardamom-based agroforestry soils were composed of silty clay loam. Mean bulk density of 0–30 cm soil from three study sites was comparatively higher in forest-based agroforestry. Soils were most acidic in *Alnus*-cardamom agroforestry systems followed by forest-cardamom systems. In the other stands, soil pH was higher (6.23–6.54). Organic C was highest in forest-cardamom, while total N and P concentrations were highest in *Alnus*-cardamom and low in farm-based agroforestry. The range of soil organic C, total P and total N availability was found to be highest in cardamom-based systems. Forest-based systems ranked second in organic C and total N, while soils from farm-based systems yielded higher total P than forest-based systems. Available P proved highest in the forest-cardamom, followed by farm-farm-based and then forest-based agroforestry

Table 8.3 Stand soil characteristics and nutrient availability

Soil parameters (at 0–30 cm depth)	Agroforestry systems				
	Farm-based	Forest-based	*Alnus*-cardamom	Forest-cardamom	*Albizia*-mixed tree-mandarin
Soil texture	Sandy loam	Sandy loam	Silty clay loam	Silty clay loam	Silty loam
Bulk density (g cm^{-3})	0.87 ± 0.02	1.27±0.05	0.98±0.05	0.76±0.03	0.82±0.03
pH	6.54 ± 1.45	6.34 ± 1.64	4.56 ± 1.21	5.38 ± 1.43	6.23 ± 1.21
Moisture (%)	28.87 ± 7.27	16.76 ± 2.12	30.12 ± 6.23	27.86 ± 4.27	21.34 ± 5.32
Total organic C (%)	1.75 ± 0.45	3.68 ± 0.38	3.78 ± 0.61	2.78 ± 0.62	2.74 ± 0.45
Total N (%)	0.21 ± 0.09	0.27 ± 0.10	0.29 ± 0.11	0.26 ± 0.09	0.27 ± 0.01
Total P (%)	0.13 ± 0.08	0.12 ± 0.08	0.16 ± 0.09	0.10 ± 0.02	0.10 ± 0.006
Available P (%)	0.006 ± 0.001	0.007 ± 0.002	0.006 ± 0.002	0.008 ± 0.002	0.007 ± 0.001
Soil nutrient contents					
Organic C (Mg ha^{-1})	59.32 ± 23	77.54 ± 32	90.51 ± 24	92.58 ± 42	62.63 ± 21
Total N (Mg ha^{-1})	3.12 ± 1.21	4.36 ± 1.51	7.65 ± 2.21	5.44 ± 1.54	4.40 ± 1.51
Total P (Mg ha^{-1})	1.13 ± 0.54	1.34 ± 0.86	1.02 ± 0.79	1.24 ± 0.82	1.26 ± 0.42
Available P (kg ha^{-1})	138.52 ± 102	130.00 ± 104	164.26 ± 114	137.51 ± 65	144.54 ± 67

Values are means of three site replicates (±SE; $n = 9$)

ANOVA for nutrient concentration: sites, Mamley, Sumik and Kabi; stands, agroforestry stands; pH, sites NS, stands $p < 0.0001$, sites x stands NS; moisture, sites NS, stands $p < 0.0001$, sites x stands $p < 0.0001$; organic C, sites NS, stands $p < 0.0001$, sites x stands $p < 0.005$; total N, sites NS, stands $p < 0.0001$, sites x stands $p < 0.005$; total P, sites NS, stands $p < 0.0001$, sites x stands $p < 0.005$; available phosphorus, sites NS, stands $p < 0.0001$, sites x stands $p < 0.0001$, NS depicts "not significant"

systems. Moisture content, as a product of the soil water holding capacity (WHC) attributed to organic C, was also highest in the *Alnus*-cardamom systems. Soil loss in cardamom-based agroforestry was lowest (32 kg ha^{-1}), while forest-based had higher (40 kg ha^{-1}), and soil loss in *Albizia*-mixed tree-mandarin agroforestry was highest (480 kg ha^{-1}) (Sharma et al. 2016b).

5 Household Livelihood Option and Income Contribution

Sharma et al. (2016c) identified seven major household livelihood sources, viz. crop production, cash crop large cardamom, other cash crops (e.g. broom grass, off-season vegetables, mandarin orange, ginger), beekeeping, livestock, services/

Table 8.4 Average annual household income (in US$) and contribution of large cardamom and other crops to household economy

Household sources of income	Sumik-Khamdong	Sang-Martam	Dhanbari-Tumin	Lingee-Sokpay	Hee-Pechreak	Hee-Martam	Contribution (%)
Crop production	2.81	52.38	127.60	11.23	22.22	22.79	1.38
Large cardamom	469.23	206.41	155.80	1216.79	955.84	2037.04	29.2
Other cash crops	6.60	189.26	4.28	25.39	20.66	13.67	1.51
Beekeeping	9.71	0.00	0.00	11.60	2.85	0.00	0.14
Livestock	275.34	278.39	426.08	188.09	178.77	789.03	12.37
Services/remittances	1368.30	1462.14	1492.55	879.12	1381.76	2578.35	53.07
Labour/MGNREGA	96.35	9.53	99.64	36.63	94.02	65.24	2.33
Total	2228.34	2198.10	2305.95	2368.86	2656.13	5506.13	100

Based on Sharma et al. (2016b); calculated as per 2015 rates
1USD = INR 65
MGNREGA, the Mahatma Gandhi National Rural Employment Guarantee Act, is a flagship program of the Government of India aimed at enhancing the livelihood security of rural households by guaranteeing 100 days of wage employment in a financial year (http://nrega.nic.in/netnrega/home.aspx accessed 12 November 2016)

remittances and labour/MGNREGA (Table 8.4). Of these, employment and remittances contributed the most to household income (53.07%). Large cardamom was found to be the second largest contributor at 29.20%, generating an average income of US$ 911 year^{-1} household^{-1}, followed by livestock, which contributed 12.37%. The remaining sources of income were other cash crops, beekeeping, off-farm labour and employment under the MGNREGA, which together contributed only 4% of household income.

Among the five different locations, Sharma et al. (2016c) studied in East, South and West districts of Sikkim. The annual household income of large cardamom farmers was highest at Hee-Martam (US$ 5965), followed by its adjacent village Hee-Pechreak (US$ 2877) which is accredited to the cultivation of the new disease-tolerant and high-yielding local cultivar *seremna*, supported by income from services/remittances. The farmers raise nurseries of *seremna* cultivars and supply good-quality planting materials to progressive farmers and to the Horticulture Department Government of Sikkim and Spices Board at Gangtok to generate cash income. They also sell planting materials to Northeast Indian states on premium prices. The contribution of large cardamom to household income was only 7, 9 and 21% in Dhanbari-Tumin, Sang-Martam and Sumik-Khamdong, respectively, while in Hee-Pechreak, Hee-Martam and Lingee-Sokpay, it was much higher at 36%, 37% and 51%, respectively (Fig. 8.6). The low contribution of household income by cardamom in Dhanbari-Tumin, Sang-Martam and Sumik-Khamdong was due to the lack of access to good planting material such as *seremna* (Hee-Pechreak,

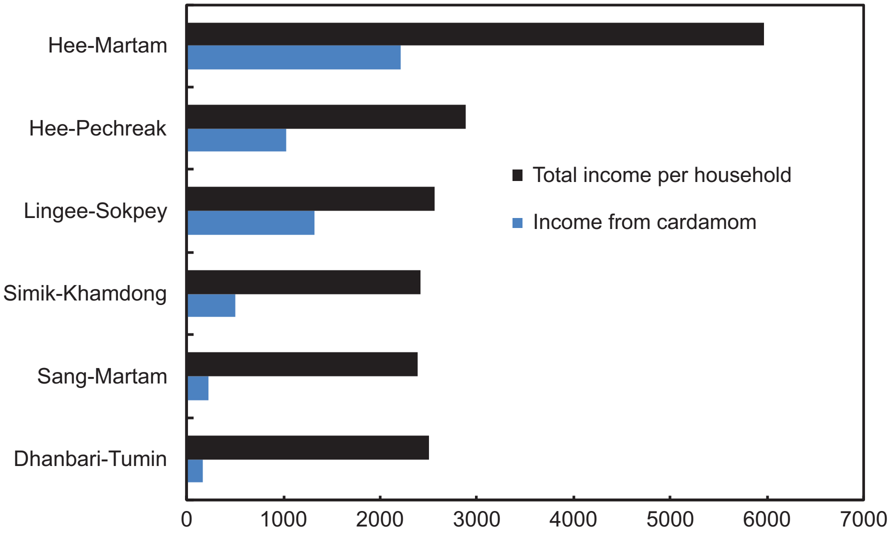

Fig. 8.6 Total household income from different sources and contribution of large cardamom to households (Amount in USD)

Hee-Martam) or *Dzongu-golsai* (Lingee-Sokpay) and feeble management practices. The contribution of services/remittances was comparatively high, ranging from 37 to 67%.

Based on agronomic yield on a per hectare basis across the locations discussed above, the income from large cardamom ranged from US$ 3246 to 5610 (US$ 24 kg^{-1} at 2014 market prices). One-way analysis of variance showed significant variation among the range of livelihood options across the six study sites ($F_{6,35} = 15.54$, $p \leq 0.001$). Of the total number of labourers employed in farming, large cardamom farming was comparatively less labour intensive (10–15%), while other farming options were highly labour intensive (85–90%) (Sharma et al. 2016c).

Cardamom was the second largest contributor to household income after services and remittances (Table 8.4). Sharma and Sharma (1997) reported that the contribution of large cardamom to household income was 45% for small households and 54% for larger households. However, this contribution declined from 50% in 1997 (Sharma and Sharma 1997) to 38% in 2000 (Sharma et al. 2000), while in 2014 it had dropped to 29% (Sharma et al. 2016c).

6 Cost-benefit Analysis of Homegarden Agroforestry

Sharma et al. (2016b) have analysed in detail the cost benefit of different agroforestry system (Table 8.5). The main inputs of energy were in the form of human labour (and oxen for ploughing, conversion 1 ox = 2 men) for land preparation,

Table 8.5 Cost-benefit analysis of homegarden agroforestry stands

Input/output	Farm-based agroforestry Energy	Farm-based agroforestry Cash	Forest-based agroforestry Energy	Forest-based agroforestry Cash	*Alnus*-cardamom agroforestry Energy	*Alnus*-cardamom agroforestry Cash	Forest-cardamom agroforestry Energy	Forest-cardamom agroforestry Cash	*Albizia*-mixed tree-mandarin agroforestry Energy	*Albizia*-mixed tree-mandarin agroforestry Cash
Input										
Labour (land preparation)	115.50	260.58	15.12	23.43	–	35.43	–	45.43	60.75	98.56
Weeding	18.75	35.54	–		4.50	30.46	6.00	31.56	26.25	48.54
Harvest	31.50	55.36	10.75	17.68	5.25	29.86	6.75	61.43	19.50	60.82
Postharvest	6.75	11.67	–		10.50	54.78	11.25	58.65	7.50	23.54
Fuelwood collection	8.25	21.87	9.45	16.87	14.76	30.54	9.65	30.54	6.12	14.87
Fuelwood for curing	–	–	–	–	1154.12	49.42	769.33	52.34	–	–
Total	180.75	385.02	35.02	57.98	1189.13	230.49	802.98	279.95	120.02	246.33
Output										
Agronomic yield	1242.03	743.76	–		712.32	**2461.21	466.08	1243**	1361.87	1187.89
Fuelwood extraction	634.47	26.87	3095.42	165.67	3127.12	156.23	1876.20	190.54	36.52	16.34
Fodder (tree/ground)	650.64	12.43	876.49	16.78	–	–	612.34	–	532.87	9.54
NTFP/wild edibles	298.53	9.64	453.67	37.87	65.37	13.41	67.45	14.56	287.73	7.89
Total	2825.67	792.70	2390.95	220.32	3904.81	2630.64	3022.07	1448.10	2605.59	1221.66
Output/input ratio	15.63	2.06	68.27	3.80	3.28	11.41	3.76	7.57	21.70	4.96

Values are pooled from three site replicates. Energy = (×10^4 kJ ha^{-1}; cash US$ ha^{-1}) (Calculated based on 2016 rates; based on Sharma et al. 2016c)
Human labour, 1 h = 0.15 × 10^4 kJ (Freedman 1982)
**Calculated at US $ 25.68 per kilogramme of cardamom as per 2015 average rate; cash conversion at US $ 1 = Indian Rupees 65

weeding and postharvesting. Inputs were high in the labour-intensive farm-based and *Albizia*-mixed tree-mandarin agroforestry, while inputs were low in cardamom-based systems. Cash inputs were thus relatively high in both. The high energy requirement for curing cardamom was met from the same system. The energy inputs in the form of human labour in comparison were very less in cardamom-based and least in farm-forest-based agroforestry. Human labour input in cardamom-based systems hovered around 33.65–35.01 × 10^4 kJ ha^{-1}, which was comparatively low. Energy inputs as human labour in farm-based and *Albizia*-mix tree-mandarin agroforestry were high (172–181 × 10^4 kJ ha^{-1}).

The main outputs of the systems were analysed in the form of agronomic yield, fuelwood, fodder and NTFP extracted during 2 consecutive years (2013 and 2014), and values were pooled. Energy contribution as fuelwood was highest from *Alnus*-cardamom, followed by farm-forest-based and forest-cardamom system. The total energy outputs from the agroforestry systems analysed were relatively close between 2606 and 3905 × 10^4 kJ ha^{-1}. The highest energy output was recorded from *Alnus*-cardamom and lowest in *Albizia*-mix tree-mandarin agroforestry. Output in the form of cash was US$ 2630.64 in *Alnus*-cardamom, 11.9 times that of forest-based, 3.3 times that of farm-based, 2.15 times that of *Albizia*-mixed tree-mandarin and approximately 1.8 times that of forest-cardamom agroforestry.

Consequently, the output/input ratio for energy was highest in the farm-forest-based system (68.27) – about three times that of *Albizia*-mixed tree-mandarin and four times that of farm-based agroforestry – whereas the other systems had much lower ratios (3.28–8.45). Output/input ratios in the form of cash were clearly the highest in cardamom-based agroforestry (*Alnus*-based systems having the highest) and proved to be the most energy efficient and economically prosperous for the communities, as well as the most cost-effective among all agroforestry systems (Table 8.5). The ratio in *Albizia*-mixed tree-mandarin agroforestry (4.96) was lower than in forest-cardamom (7.57) and provided a relatively good economic return. This clearly reflects that the cardamom-based and *Albizia*-mixed tree-mandarin agroforestry provide sustainable economic benefits as both the crops are comparative advantage crops with established international market, while other agroforestry systems provide a variety of resources including food (Sharma et al. 2016b).

7 Indicators of Climatic Variables and Impacts

The indigenous communities in the Sikkim Himalaya have perceived changes in the climatic conditions over time – they are experiencing different levels of climatic variation over several decades – in the form of erratic rainfall/snowfall events, prolonged dry spells or droughts, warmer winters, unpredictable monsoon, disappearance of local springs, emergence of new diseases and pests in crops/fodder trees, etc., and these changes are expected to persist in the future (Sharma and Rai 2012). Such events are posing potential future risks such as growing food and livelihood insecurity, dependence on cash-based income, increased drudgery, degradation of plantations of large cardamom and mandarin orange, crop failure, scarcity of water for drinking and irrigation, migration of farm labour and increased workload to elderly people and women, increasing health problems, etc. The small farming communities in the Sikkim Himalayan region are vulnerable to geographic exposure, low incomes, greater reliance on agriculture as well as limited capacity to seek alternative livelihoods, which if not addressed is expected to accelerate at a fast rate.

In the last 7 years (2010-2017), the popular "Dhara Vikas" initiative of Rural Management and Development Department of Government of Sikkim, The Mountain Institute India and other partners has been implemented to revive drying springs, streams and lakes and has shown considerable success, with the revival of 50 springs and 4 lakes in 20 drought-prone gram panchayats – showing promising results and the potential to be scaled up and mainstreamed in ongoing programs in the Himalayan region (Sharma 2012; Tambe et al. 2012, 2013) and is expected to support water requirement in traditional farmlands.

However, traditional farmers are designing and redesigning TFS into a resilient system to build up the adaptive capacity of these agroecosystems through their ecological knowledge systems. One example of building resiliences is the identification of drought-tolerant species, or shade-tolerant species, or exchange of seeds of cereals, tubers, ginger, pulses, potatoes and even fodder trees from lower to higher altitudes and vice versa to accommodate species that are best suited to particular microclimatic conditions. Farmers often exchange farmlands for a variety of suitable crops for enhancing productivity. Traditionally managed agroforestry systems are rotational; an example is large cardamom plantations in the forests under TFS are at declining phase over the last 15 years, while cultivation of broom grass, fodder tees, medicinal plants and ginger cultivation is taking over. Immediately, farmers have brought large cardamom which is a high-value, less labour-intensive cash crop to the surrounding of the homegardens with additional inputs such as manure, irrigation and management of diseases and pests. The agroecosystems are subjected to anthropogenic pressures such as rapid land use change (development activities such as road construction, hydropower construction, establishment of industries, etc.) and introduction of exotic crop varieties (high-yielding varieties/hybrids of rice, maize, wheat, pulses, fruits such as kiwi, medicinal plants such as Korean ginseng, etc.), thus increasing the fragmentation and degradation of the natural habitat of the indigenous species. Such human-induced pressures are resulting in progressive loss of agrobiodiversity. Landraces of rice, maize, pulses, ginger, wheat, buckwheat finger millet, yams and pumpkin are rapidly disappearing due to climate change impacts.

In TFS, many methods are used to maintain soil productivity such as intercropping, crop rotation and fallowing. Farmers often replace or exchange seeds or farms to experiment with suitability and resilience under changing agro-environmental conditions. These practices continue to ensure food and livelihood security in the face of increasing climate change and variability. The promotion of diverse homesteads in traditional farming systems would ensure family food supply in areas significantly affected by climate change. For the Sikkim Himalaya, two types of adaptation strategies for enhancing the resilience of homesteads can be planned: (1) in drought-prone regions, the resilience of traditional homestead gardens is strengthened through the intercropping of fruit trees with vegetables, micro-irrigation and organic fertilizers; and (2) improvement of animal husbandry for livestock production involving local or traditional breeds (such as *siri* breeds of cow) would enhance the household economy and manure production in areas with low productivity.

8 Changing Adaptation Dimension in Traditional Farming Systems

Management dimensions vary in different mountain land use systems. Agroforestry systems in the traditional mixed farming in the Sikkim Himalayas have high ecological adaptability, resilience and opportunities for sustainability. These agroforestry systems have been a source of food and environmental security for resource-rich cash-poor marginal farmers due to market constraints. Given the opportunities of market and technology, the traditional communities would be able to trade agroforestry products to national, international markets, while they also contribute to reduce global warming through carbon consumption in these agroforestry systems they have established over time. The example is large cardamom-based, farm-based and farm-forest-based agroforestry system where a diversity of trees is grown for their multiple functions.

8.1 Socioecological Dimension

Agricultural systems are embedded in wider social-ecological processes that must be considered in any complete discussion of sustainable agriculture (Bacon et al. 2012). The TFS in the Sikkim Himalayas are dependent on wider social-ecological processes that contribute to sustainable agriculture due to a variety of functions (Table 8.6). In the context of traditional management of agroecosystems in the Eastern Himalayan region, the ecological dimension is entirely embedded in the social dimension, and thus both are interrelated. The management of agriculture system as such is an integral nexus of ecology and society with time and represents coevolution of nature and culture, humans and landscape (Zimmerer and Bassett 2003; Wells 2011).

The soil and nutrient loss from the agroforestry system is comparatively low as these systems do not require intense tillage, while the loss is high in traditional open-crop mixed farming system where loss is due to wet rice cultivation. All these traditional farming systems house rich biodiversity (medicinal plants around 200 species, fruits 48 species and several fodder and timber species, cereals, tubers, underutilized species, etc.) (Sharma 2016; Sharma et al. 2016a). Sharma et al. (2016a) reported an assemblage of diverse gene pools that consist of more than 126 landraces of cereals including rice (77), maize (26) and millet (7); 18 cultivars of oilseeds; 34 cultivars of pulses and beans; 132 species of vegetables; 38 spices/

Table 8.6 Socioecological dimensions of management options required for principal land use systems in the Sikkim Himalayas

Dimensions and factors	Farm-based agroforestry	Forest-based agroforestry	Large cardamom-based agroforestry	Traditional open-crop mixed farming
Soil loss/nutrient loss	Low	Low	Very low	High
Irrigation	Rainfed	Rainfed	Irrigated/rainfed	Irrigated/rainfed
Carbon sequestration	Very high	Very high	Very high	High
Soil fertility maintenance	Maintained within the system	Maintained within the system	Maintained within the system	Maintained within the system
Biodiversity	Very high	Very high	Tree diversity high	Agrobiodiversity high
Colonization of alien species	High	Very high	Less	Very high
Incidence of diseases/pests	High	Low	Very high	Very high
Greatest challenge for farmers at present	Land degradation, productivity decline	Shrinking land availability	Management of viral/fungal infestation in large cardamom and soil moisture	New disease management
Ecological complexity, resilience and functioning	Complex, ecologically fragile	Complex, ecologically sustainable	Complex, ecologically sustainable	Complex, ecologically fragile
Water source conservation	Springs are conserved/are sacred	Catchment for recharge of springs	Catchment for recharge of springs	Springs are conserved/are sacred
Dynamics	Rotational	Rotational	Rotational	Dynamic and rotational

condiments; and 33 landraces of tubers/roots. As many as 64 fruit tree species are commonly grown on farms, with more than 200 species of wild edibles naturally growing in the region's farm-based, forest-based and large cardamom-based agroforestry land. The TFS also house a rich diversity of protein banks with a total of 14 landraces of "rajma" (kidney beans) and 7 landraces of rice beans, as well as 20 landraces of chillies, 55 landraces of squash and 4 landraces of ginger. More than 119 species of multipurpose agroforestry trees (used for timber, fuelwood, fibre, fodder, dye, soil binders in terraces, minor construction materials, etc.) have been recorded. While 52 crop species have high social and cultural importance, 69 other species are sacred to indigenous communities (Sharma et al. 2016a).

Livestock is an integral part of the TFS, and manure production is key to maintenance of soil fertility which is added to the farm at various crop seasons mostly in the traditional open-crop mixed farming, while over the last 5 years, farmers have started adding manures to cardamom for better production. Farmers reported that invasive alien species such as *Chromolaena adenophorum*, *Chromolaena odoratum*, *Bidens biternata*, *Artemisia nilagirica*, *Lantana camara*, *Ageratum conyzoides*, *Cestrum auranticum*, *C. fasciculatum* and *Galinsoga parviflora* have caused serious problems in the farmlands, forests, traditional agroforestry systems, fallow lands, croplands and wetlands (Sharma and Dhakal 2011).

It is interesting to note that, in a TFS and since Sikkim is an organic farming state of India which is the forerunner on this concept, soil fertility has been maintained by repeated addition of various amounts of organic compost/manure, ranging from 1 to 15 Mg ha^{-1} $year^{-1}$ (Sharma and Rai 2012). The highest amount of manure is required for ginger (1–15 Mg ha^{-1} $year^{-1}$) followed by vegetables (8–12 Mg ha^{-1} $year^{-1}$) and large cardamom (7–12 Mg ha^{-1} $year^{-1}$) which is applied twice a year. Large amounts of compost are produced from a mixture of livestock manure, forest leaf litter and farm waste.

8.2 Socio-economical Dimensions

The Sikkim Himalayan TFS is passing through a process of transformation due to the process of globalization: the traditional system of farming versus the modern concept of organic farming, cash crop-based farming initiatives, introduction of high-yielding varieties and finally conversion of cultivated lands into development sector for construction such as pharmaceuticals and hydropower (Table 8.7). Farm labour migration for lucrative jobs in the cities and town within and outside the state has constrained farm families to continue farming; several abandon lands without rice cultivation can be seen. The farm labour cost in 10 years of time increased by 100–200%, and farm management cost has increased >200% in 20 years time.

Table 8.7 Socio-economical dimensions of management options required for principal land use systems in the Sikkim Himalayas. FBA, FoBA, LCBA and TOMF

Dimensions and factors	Farm-based agroforestry	Forest-based agroforestry	Large cardamom-based agroforestry	Traditional open-crop mixed farming
Labour requirement	High	Low	Medium	Very high
Manure requirement	Very high	Low	Medium	Very high
Management cost	Very high	Low	Low	Very high
Production potential of crops	Medium	Medium	Very high	Very high
Labour availability for farming	Very low	Very low	Very low	Very low
Yield benefits (monetary)	Medium	High	Very high	Very high

Agroforestry is a landscape-scale approach, thus favouring synergy between adaptation and mitigation. In the indigenous farming systems of the Sikkim Himalayas – multipurpose trees are grown, and the cereals, legumes, tubers, cash crops and a variety of ground fodder are managed together which is unique. These are closed-loop systems where external input is nil, for example, the shade-tolerant crops adapted to particular tree species or a combination of tree species, trees and crops with nonoverlapping roots and trees and crops with temporally differentiated ecological requirements (e.g. dry and wet season).

8.3 Sociocultural Dimensions and Sustainability

The diversity of ethnic communities and management approaches in the landscapes reveal that culture is significantly linked to agroforestry practices (Table 8.8). In homegarden agroforestry systems, the significance of culture arises since culture is the fabric of every community that shapes "the way things are done and our understanding of why this should be so" (CIDA 1995). The concept of culture is an integration of components and is the sum of "complex whole of knowledge, wisdom, values, attitudes, customs and multiple resources which a community has inherited, adopted or created to flourish in the context of its social and natural environment" (Verhelst and Tyndale 2002). The specific sociocultural dimensions as illustrated in this study include management approach, cultural values of practices, cropping system and harvesting, conservation approach, adaptability and organizational capacity of the ethnic cultural societies. In the TFS, sharing and exchanging of farm labour and planting materials of adaptive species increase in dependency diversity of species as per the variety of requirements, farmers' self-reliance and social harmonization.

Livestock in an integral part of TFS and thus manure production for the farms, milk and milk-based products or meat products serve the purpose of cash earning. Mountain farmers have identified and employed a wide variety of plant species suitable at location-specific altitudinal gradients that are adaptive and that are yet not very much impacted by climatic variation. Fruits cultivated in the farm are good source of income to the local and indigenous communities in Sikkim. In Sikkim moderate to high level of food insecurity exists given the conditions of mountain specificities such as fragility, marginality, inaccessibility and climatic variations. There are examples of production losses that occur to many natural phenomena including but not limited to drought, heavy snowfall, hailstorm, flood and landslide disasters. Tree species such as alder (*Alnus nepalensis*), *badar* (*Artocarpus lakoocha*), as many as five different species of *siris* trees (*Albizia stipulata*, *A. microphylla*, *A. odoratissima*, *A. procera*, *A. lebbeck*), *gayo* (*Bridelia retusa*), *khari* (*Celtis tetrandra*), pipli (*Exbucklandia populnea*), *Chilauney* (*Schima wallichii*), *panisaaj* (*Terminalia myriocarpa*), *lekh-saur* (*Betula utilis*), as many as seven species of fig trees (*Ficus nemoralis*, *F. glomerata*, *F. benjamina*, *F. cyrtophylla*, *F. benghalensis*, *F. elástica*, *F. religiosa*), *lek-bohori* (*Ehretia wallichiana*), etc. are socioculturally and socio ecologically important.

Table 8.8 Sociocultural dimensions and sustainability of management options required for principal land use systems in the Sikkim Himalayas

Dimensions and factors	Farm-based agroforestry	Forest-based agroforestry	Large cardamom-based agroforestry	Traditional mixed farming
Sociocultural dimensions				
Management approach	Multipurpose trees and understorey crops	Multipurpose trees, bamboo groves grown	Shade trees and understorey cardamom grown	Trees and understorey crops grown
Cultural values of practice	Very high	Very high	Very high	Very high
Cropping pattern	Two times or more	Tree crops and NTFPs	One understorey crop	Two times or more
Postharvest technology	Traditional, multiple harvest	Multiple harvest	One-time harvest	Traditional, multiple harvest
Livestock integration	Livestock as a part of practice	Grazing/fodder for livestock	No livestock	Livestock as a part of practice
Adaptability of the system	Very high	Very high	Very high	Very high
Organizational capacity	Very High	Very high	Very high	Very high
Conservation approach	Food sustainability	Cultural importance, often private sacred forest	Economic return	Economic return and food
Sustainability	Multipurpose trees and crop diversity conserved	Multipurpose trees, wild edibles/NTFP diversity conserved	Large cardamom genetic diversity conserved	Multipurpose trees and crop diversity conserved
Dynamics	Rotational	Rotational	Rotational	Dynamic and rotational

These agroforestry systems are highly dynamic; the indigenous farmers manage and transform land use as per requirement over period of time. At the wake of climate change when productivity of the cereal crops or cash crops are not enough, the conversion of some parcel farmland into agroforestry by growing fodder, fruit trees or medicinal plants have been initiated as an adaptive practice.

9 Emerging New Policy Paradigms

As per the India's National Policy for Farmers (2007), the agriculture sector contributes only about 18% of the total gross domestic product (GDP), with more than 60% population dependence, resulting in low per capita income in the farm sector, while there is a large disparity between the per capita income in the farm sector and the nonfarm sector. In addition to this, there are several constraints such as preponderance of small and marginal holdings accounting for about 82% of total holdings; imperfect market conditions and lack of backward and forward linkages affect the income levels of farmers adversely. Therefore, an appropriate policy on mainstreaming agriculture practices into policy guideline was needed to be evolved to ensure that farming activity becomes more viable and the economic condition of farmers is improved on a sustainable basis.

The approved National Agriculture Policy of the Government of India during 2000 was aimed to achieve annual growth of more than 4% in the agriculture sector on a sustainable basis, through the efficient use of natural resources and combination of other measures; however, the annual growth rate achieved during the Tenth Five-Year Plan (2002–2003 to 2006–2007) averaged around 2.3%, while the nonfarm sector grew faster. During 2015–2016, agriculture contributed 17.4% to GDP of India, as compared to 18.3% in 2013–2014. Comparing the 12th Five-Year Plan for 2012–2017, the target of 4% growth in the agriculture and allied sectors, the growth registered was 4.2% in 2013–2014, −0.2% in 2014–2015 and estimated 1.1% in 2015–2016 (KPMG 2016). It is paradoxical to mention that the National Policy for Farmers (2007) has envisaged “Tribal Farmers” to priorities uplifting of their economic condition; it has not developed the framework for upscaling of the existing TFS that has given employment and livelihoods to indigenous farmers in the country.

The Indian Sikkim State Government in 2003 declared to convert entire agricultural land under practices into fully organic by 2015, and consequent to this Sikkim State Organic Mission was launched in 2010 (FSAD and HCCD 2010). As per the Executive Director, Sikkim Organic Mission, the entire 74,343 ha (10.47% of the total area of the state) of cultivable land has been certified as organic and thus making Sikkim as the first organic farming state in India. The declaration of the Sikkim Organic Mission by the Government of Sikkim in 2010 was made with the objective of addressing the basic requirements of an organic crop production system, wild crop harvesting, organic livestock management and processing and handling of organic agricultural products (Bhutia 2015). Given the ambitious framework developed by the Sikkim Government, the organic agriculture with due recognition of TFS is expected to bring in opportunities for indigenous mountain farmers in Sikkim. A few benefits have been outlined in the organic policy document of the Government of Sikkim, some of them are improvement of soil physical, chemical and microbiological conditions, improvement of soil flora and fauna, efficient water usage, improvement of livestock as an integral part of organic farming, improvement of agrobiodiversity including biodiversity in general, protection of traditional knowledge systems, fetch premium prices for organic produce and finally improvement of the overall sustainability of the agriculture systems (FSAD and HCCD 2010).

The Sikkim Biodiversity Action Plan (2012) highlights strategies recommended for agrobiodiversity conservation, protection and promotion. It has given a set of responsibilities, with corresponding time frames, to research and development agencies (e.g. Indian Council of Agricultural Research (ICAR), National Bank for Agricultural and Rural Development (NABARD), National Biodiversity Authority, Department of Agriculture Research and Education under the Ministry of Agriculture and Farmers Welfare and the National Bureau of Animal Genetic Resources), including the Agriculture, Horticulture and Animal Husbandry Departments of the Government of Sikkim, to ensure that markets are available for organically farmed local crop varieties (SBAP 2012).

An increasing number of small-scale farmers in Sikkim have adopted bio-composting or vermicomposting – nontraditional methods of improving the nutrient content and water holding capacity of the soil. Mulching, the use of nitrogen-fixing species, and the application of farmyard manure and green manuring are traditional methods for enhancing soil fertility – improvement in this sector is yet to more receive attention. Agriculture is mostly rainfed, and high-value cash crops such as large cardamom, off-season vegetables and fruit crops such as mandarin orange, kiwi, guava, peach, pear, plum, banana, etc. require adequate soil moisture and irrigation facility to augment high productivity. Farmers' friendly techniques can improve the cultivation of stress-tolerant crops, crop diversification and productivity. Both traditional and innovative farm techniques can strengthen the resilience of local food systems.

10 Conclusion

The cultivated landscapes in the Sikkim Himalayas are indigenously managed mosaics of TFS, which is a treasure trove of agricultural biodiversity and is a part of one of India's agrobiodiversity hotspots. Over the years, the process of globalization has posed a grave threat to TFS of the Sikkim Himalayas. Monocultures and cash crop-based farming are spreading in market-connected villages (organic agriculture) and high-yielding hybrids taking over the traditional landraces, while development activities are rapidly converting the agricultural lands to nonagriculture sector. Poor scientific understanding of TFS and related sociocultural/socio-economic issues and lack of appropriate policy for promotion and conservation of "original agriculture systems" seriously impede the identification of solutions for sustainable agricultural development in the region.

Agroforestry systems play a significant role in sequestering carbon and contribute to mitigate climate change; thus, there are opportunities for carbon financing which is yet to be realized for payments for environmental services. The best that can be done is to support efforts by smallholder farmers to enhance and improve homegarden agroforestry wherever possible. Long-term solutions demand greater political commitment, policy development and enforcement, a participatory approach and a bottom-up approach. The "Organic Mission" of the Government of Sikkim to convert the entire Sikkim into organic is one of the steps that is expected to enhance farmers livelihood strategies particularly in areas under high ecological, climatic and economic stresses and risks. This mission is also expected to empower farming communities which is essential for effective in situ or on-farm conservation. This process will ensure and encourage farm-level decision-making on management of genetic resources and associated traditional knowledge. Moreover, additional research is required to quantify the benefits to various stakeholders, to increase household income, to promote gender equity, to empower women, to improve the health and welfare of people and to promote environmental sustainability especially in the Eastern Himalayan region.

This study confirmed that NTFPs from agroforestry present a valuable source for household economies, as well as for augmenting the household diet. Soil loss in cardamom-based agroforestry was lowest, while forest-based had higher, and soil loss in mandarin-mix tree-based agroforestry was highest. Large cardamom was found to be the second largest contributor (29.20%) of household income, generating over US$ 911 year^{-1} household^{-1}, followed by livestock, which contributed 12.37%. The remaining sources of income were other cash crops, beekeeping, off-farm labour and employment under the MGNREGA, which together contributed only 4% of household income. The output/input ratio for energy was highest in the forest-based system (68.27) – about three times that of *Albizia*-mix tree-mandarin and four times that of farm-based agroforestry – whereas the other systems had much lower ratios (3.28–8.45). Given the opportunities of market and technology, the traditional communities would be able to trade agroforestry products to national and international markets, while they also contribute to reduce global warming through carbon consumption in these agroforestry systems they have established over time.

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Chapter 9
Horticulture-based Agroforestry Systems for Improved Environmental Quality and Nutritional Security in Indian Temperate Region

Brahma Singh and Sanjai K. Dwivedi

Abstract The temperate region represents 18% of the India's land area. The region stretches from Arunachal Pradesh in the east up to the mountains of Jammu and Kashmir in the west. Importance of agroforestry can hardly be overemphasized in this region as it caters the local requirement of fuel, fodder, timber, bio-fence, checking soil erosion, etc. Horticulture-based agroforestry in temperate region would be complimentary and supplementary to temperate horticulture which has been documented in this article. The different types of agroforestry having horticulture crops in temperate regions of India have been listed. Agroforestry systems in northeast, western, and central Himalayan states have been discussed. Certain issues in temperate agroforestry such as lack of proper policy regime, knowledge gaps of technical know-how of the existing systems, low yield of the existing systems, lack of efficient utilization of space and time, only few limited tree species that are grown and low adoption of agroforestry systems, small and scattered landholdings, and lack of irrigation facility have been mentioned. Lack of advocacy on agroforestry in temperate regions is restricting its popularity. The chapter covers cold desert areas of the country.

Keywords Horticulture · Agroforestry · Temperate region · Environment · Nutrition security

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1 Introduction

Chemical agriculture has created adverse conditions to look for suitable agriculture system which improves environment, ecology, and economic condition of farmers. Agroforestry is one of the similar systems. The requirement of sustainable and environmentally sound and highly productive agricultural systems has led to a renewed interest in agroforestry practices in temperate regions. The major objectives for establishing agroforestry systems in temperate regions are also somewhat similar as in tropical region like production of tree or wood products, agronomic crops or forage, and livestock, improvement of crop quality and quantity, etc. Major emphasis is on added environmental benefits and nutritional security.

To attain above objectives, enhancement of microclimatic conditions; improved utilization and recycling of soil nutrients; control of subsurface water levels; improved soil and water quality; provision of favorable habitats for plant, insect, or animal species; soil stabilization; and protection from wind and snow, among other suitable management practices, are adopted. Horticulture practices involving cultivation of fruits, vegetables, flowers, medicinal aromatics, and spices in temperate region are preferred because of high production potential and quality produce. Horticulture husbandry is known to provide nutritional security and improve environment. Horticulture-based agroforestry in temperate region would be complimentary and supplementary to temperate horticulture which is being documented in this article.

2 The Temperate Regions of India

The Indian Himalayas represent 18% of the India’s land area. It occupies a special place in mountain ecosystems of the world. This region is not only important from the standpoint of climate and as a provider of life, giving water to a large part of the Indian subcontinent, but it also harbors a rich variety of flora, fauna, human communities, and cultural diversity. Dispersed small settlements and terraced agricultural fields carved out of the hill slopes for raising crops, numerous multipurpose tree species growing, particularly on the boundaries of rain fed terraces, are typical in the temperate area of Himalaya (Mughal and Bhattacharya 2002). India is a diverse country in every respect. From climatic conditions point of view, India has six major climatic zines, viz., tropical rainy zone, humid subtropical zone, tropical savanna zone, steppe climatic zone, mountain/temperate zone, and dessert zone. This article covers only temperate zone of Himalaya. This temperate zone is comprised of alpine, temperate subalpine, subtropical hill, subtropical plain, mild tropical hill, and mild tropical plain zones (Banyal et al. 2011). The region stretches from Arunachal Pradesh in the east up to the mountains of Jammu and Kashmir in the west. The states of Arunachal Pradesh, Sikkim, Uttarakhand, Himachal Pradesh, and Jammu and Kashmir are major states under temperate zone. This zone has varied climatic conditions, major climates being high humid and cold arid/dessert. Large area of Himachal Pradesh (Lahaul and Spiti) and Jammu and Kashmir (Ladakh) experience extremes of prolonged winter with sparse vegetation.

Agriculture is the major economic activity of the people inhabited in the Himalayan region and practiced on steep terraced slope and is very complex in that of crop husbandry; animal husbandry and forest constitute interlinked production systems. Many multipurpose tree species are conserved as scattered trees in settled farms on terraced slopes by the traditional farmers. In recent years, environmental degradation, poor resource management, and increased migration of men to plains have led to abandonment of agricultural land in the form of degraded land.

Each state in Indian Himalaya is different and distinct. Uttarakhand state forms the major part of the central Himalaya that comprises diverse agroforestry system. The major land use characteristics are forests, agriculture, seral grassland, and alpine pastures. These land use components are independent, and over a period local people have evolved agricultural practice to meet their food, fodder, and fuelwood requirement. The landholdings are mostly (70%) marginal (less than 1 ha) and small (1–2 ha). In addition, landholdings are scattered at various locations in a village. However, Sikkim state is in the eastern Himalayan region, covering an area of 7096 sq.km. The elevation ranges from 270 m (lower hills) to 8598 m (snow-bound lands), and annual rainfall ranges from 1300 mm to over 4000 m. About 80% of the population depends on agricultural land for their livelihood. Average landholding is 1.95 ha.

3 Agroforestry in Temperate Region

In India, temperate fruit cultivation is spread over 350,000 ha with an annual production of nearly 1.6 million metric ton. Apple occupies 50% of this area. It is followed by pears, plums, peaches, apricots, walnuts, and almonds. Suitable tree species are grown in and around orchards to provide additional income to farmers besides contributing to improvement in environment. Agroforestry systems in temperate regions of India offer great promise to produce biomass for biofuel, fodder, specialty and organic crops, pasture-based dairy, sheep and goat rearing, and others (Swamy et al. 2016). Agroforestry also offers proven strategies for carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement for not only the farmers, but for the society at large. Agroforestry is an environmentally sound, ecologically sustainable, and economically viable alternative to traditional farming and arboriculture. The following types of agroforestry having horticulture crops are practiced in temperate regions of India.

3.1 Windbreaks

Locally suitable tree species are planted around agriculture fields in single or double rows to mark boundaries of the fields and mainly add to farm income at an interval of few years on their timber production. Tree species in demand in the area with deciduous nature and single stem are preferred for windbreaks to orchards and other crops. They are managed as part of the crops to protect them from strong winds.

3.2 Forest Farming

Forested areas are utilized for producing specialty crops having medicinal, ornamental, culinary, fodder, fiber, oil, and other uses.

3.3 Alley Cropping

Trees are planted in single or grouped rows in agricultural or horticultural crops in the wide alleys between the tree rows. Competition between trees and crops in alley cropping systems for soil moisture, light, and nutrients, especially nitrogen, can lead to decreased productivity of the associated crop.

3.4 Riparian Buffer Strips

Strips of perennial tree/shrub/grass are planted between croplands/pastures and streams, lakes, wetlands, and ponds.

3.5 Silvi-olericulture

Integration of vegetable production with trees on the boundary or in rows in the field is common in cold arid regions.

3.6 Horti-pasture

Fruit trees pasture and/or animals are the part of this system.

3.7 Horti-olericulture

Fruit crops and vegetables are major parts of the system with fence of trees or shrubs on the boundary of the field.

3.8 Live Fence

Shrubs like sea buckthorn (*Hippophae rhamnoides*) are planted all around the fields of fruit trees, vegetables, or medicinal plants.

3.9 Silvi-horti-Sericulture

Timber, fuel, and/or fruit trees along with major crop of mulberry (*Morus alba*) are part of this system.

3.10 Horti-apiculture

Vegetables particularly seed crops, fruit trees, and beehives make the system remunerative with and without tree/shrub fence in and around the field.

3.11 Homestead

This system has multiple combinations of fuel, timber, fruit trees, vegetables, medicinal plants, and others.

4 Agroforestry in Northeastern Himalayan Region

Eight hill states in northeast region of the country are Arunachal Pradesh, Assam, Meghalaya, Manipur, Mizoram, Nagaland, Tripura, and Sikkim. This region is collectively called northeast hill (NEH) region. The region experiences high rainfall which affects flora and farming system. The climate, topography, altitudes, farming systems, and habitats are largely diverse with very little commonality. Floristic wealth being different makes it difficult to have one or two agroforestry systems in the region. Keeping in view vast and varied horticultural, tree, and animal wealth, several site-specific agroforestry systems have been worked out for the following agroclimatic zones in NEH (Bhattacharya and Misra 2003) (Table 9.1).

Table 9.1 Area under different agroclimatic zones in NEH

S. no.	Zones	Altitude (meter)	Approx. area (km^2)
1	Alpine	Less than 3500	47,068
2	Temperate subalpine	1500–3500	33,564
3	Subtropical hill	1000–1500	29,021
4	Subtropical plain	400–1000	812
5	Mild tropical hill	200–800	26,349
6	Mild tropical plain	0–200	29,333

4.1 Horticulture-based Agroforestry Systems in NEH

In NEH region trees are part of farming systems. Among horticultural crops ginger, turmeric, cardamom, large cardamom, black pepper, betel vines, pineapple, coffee, tea, and many vegetables are grown with forest and fruit trees like *Pinus kesiya*, *Alnus nepalensis*, *Schima wallichii*, *Pyrus communis*, *Prunus domestica*, *Areca catechu*, and others. The vegetables include okra, cole crops, solanaceous vegetables, leafy vegetables, legumes, root crops, and cucurbits (Swamy et al. 2016). The choice of specific tree species and intercrop depends on climatic condition of the area and economic importance of the species.

4.2 Agroforestry Models in Northeastern States of India

Horticulture-based agroforestry in northeast India holds a great potential to make a positive and significant contribution to agricultural output, besides raising food, fuelwood, timber, fodder, milk, and meat production in one way and conserving the soil and water in another. This would improve environmental and nutritional security in the region. The multipurpose tree species would contribute better. The major benefit here is that the value of tree products (such as fruit, nut, timber, or resin) is typically higher than the value of agricultural goods. Agar tree (*Aquilaria malaccensis*) has been identified as a potential agroforestry species, especially for Assam due to its abundance in northeastern region of India. Some medicinal plants like patchouli (*Pogostemon cablin*), sarpagandha (*Withania somnifera*), Brahmi (*Brahmi indica*), Mosundary (*Houttuynia cordata*), Mohavingaraj (*Wedelia calendulacea*), Narasingha (*Murraya koenigii*), etc. are selected for intercropping with Agar trees in Assam. Tea, rubber, cardamom, and coffee prefer diffuse sunlight and are most important commercial plantation crops in northeast India. These plantation crops are planted with several nitrogen-fixing multipurpose tree species (MPTS) and some compatible crops such as black pepper, betel vine, areca nut, etc. Such high-density multistoreyed plantation system is found to be profitable and acceptable by the farmers, suiting the environment to the northeastern region of India. Some vegetables are cultivated in between the fruit trees such as jackfruit (*Artocarpus heterophyllus*), citrus (*Citrus reticulata*, *C. limon*), guava (*Psidium guajava*), mango (*Mangifera indica*), coconut (*Cocos nucifera*), etc. In between the fruit trees, growing of spices such as black pepper (*Piper nigrum*), ginger (*Zingiber officinale*), turmeric (*Curcuma longa* syn. *C. domestica*), etc. has been a common practice in northeastern region of India. Above and beyond, most profitable tree species such as areca nut (*Areca catechu*), citrus (*Citrus reticulata*), and Agar tree (*Aquilaria malaccensis*) are also planted as shade tree in the tea gardens of Assam and found to be well-matched, ecologically viable, and economically most profitable system of cultivations of tea.

In a state of Meghalaya valleys with lower altitude, an agrihorticultural system, based on guava, has been reported to give 2.96-fold higher return than a comparable system without trees. Pineapple-based agroforestry is prevalent in Meghalaya and Tripura. In Assam, lemon-based agroforestry system increases the net return by 1.98-fold. Bamboo-based agroforestry systems have wide scope to be integrated on farmlands, homesteads, degraded lands, and riparian filter, in NEH. These systems are potential to augment the income of farmers besides conserving the resources efficiently. In some of the states of NEH Jhum or shifting cultivation is practiced. Horticulture-based Jhum farming system includes fruit crops like Khasi mandarin, Assam lemon, peach, litchi, guava, mango, banana, spices like cardamom, vegetables, and medicinal plants (Bhattacharya and Misra 2003). Agroforestry in NEH region is practiced mainly on lower elevations.

In Sikkim, ten different agroforestry systems are recognized on farmers' land in south and west Sikkim, which are rich in tree-crop diversity. In total 96 different plant species were recorded in agroforestry systems in Sikkim Himalayas which include 13 food crops, 32 multipurpose tree species, 11 fruit trees, 6 wild fruit trees, 30 different types of vegetables, and 4 fodder grasses of which 85% plant species are native. Out of ten agroforestry systems, agri-silvopasture, agrihorticulture, agri-hortipasture, livestock-based mixed farming systems, apiculture, and kitchen garden are the most beneficial and preferred by farmers. As per the perception of farmers, the functional unit like agricultural crops, vegetable crops, and fodder crops plays a productive role, whereas large cardamom, multipurpose tree species, pastures, fruit trees, and apiculture play both a productive and protective role. However, research on choice of species, tree-crop interaction, and spatiotemporal dynamics studies should be undertaken to get maximum benefit from the systems.

The following agroforestry systems are in vogue in NE region of India:

1. Agri-silviculture (crops + trees)
2. Agri-horticulture (crops + fruit trees)
3. Silvopasture (trees + fodder crops)
4. Horti-pasture (fruit trees + fodder crops)
5. Agri-horti-silviculture (crops + vegetable/fruit/flower crops + trees)
6. Homestead agroforestry (mixtures of crops, vegetables, fruit trees, fodder crops, and trees)

5 Agroforestry Systems in Western and Central Himalayan States

The climate in this region varies from hot and subhumid tropical in the southern low tracts to temperate cold alpine and cold arid in the northern high mountains. Annual precipitation ranges from 8 to 350 cm. Three major groups of soils, namely, mountain meadow soils, submontane meadow soils, and brown hill soils (Cryosorolls, Crychepts, Hapludalfs, Palehumults), occur. Only about 5–17% area is under cultivation. Orchards provide temperate and subtropical fruits. The region has great potential for further development of horticulture and orchards. Indiscriminate felling, overgrazing, soil erosion, and soil acidity are the main liabilities. Rich forest wealth and alpine grasslands most suitable for sheep/goat rearing and fruit gardening are the assets. The vast glaciers, after thawing, provide ample water for irrigation in the plains. Crop and animal husbandry can complement the regional economy, and allied industries can provide adequate employment opportunities.

There is growing problems of fuel, fodder, and packaging material in the western Himalaya. Several studies on agroforestry systems have been conducted in this region. In one of the studies, species composition, biomass, and productivity patterns of three types of traditional agroforestry systems, namely, agrisilvicultural, agrihorticultural, and agrihortisilvicultural, commonly practiced in the western Himalaya, were studied. Among the three systems, agrihortisilvicultural was found highly diverse in vegetation, with as many as 13 trees and 5 agricultural crops mixed together. This system showed the highest productivity up to 25.8 Mg ha^{-1} year^{-1}, out of which 68% was contributed by the trees and the remainder by the annuals. Agrisilvicultural system having predominantly annuals had the lowest productivity of 20.4 Mg ha^{-1} year^{-1} with only 27% contribution by the trees. Total aboveground biomass in agrihortisilvicultural or agrihorticultural system was around 48 Mg ha^{-1}, and it was about twofold higher than agri-silvicultural system (Rathore et al. 2013). In fodder trees, a significant percentage of annual production, up to 48%, was allocated in current twigs, while in horticultural trees a major portion, up to 63%, was portioned toward fruits. Annual fodders like lucerne or alfalfa (*Medicago sativa*) are commonly cultivated with fruit trees (Fig. 9.1).

This region grows lot of fruits and medicinal plants along with MPTS. Important medicinal herbs and fruit crops which are part of horticulture-based agroforestry are listed in Tables 9.2 and 9.3 (Thakur et al. 2010). Besides most of the temperate vegetables and flower crops are also included in such agroforestry systems.

6 Cold Desert Agroforestry

Indian cold deserts fall under Himachal Pradesh (Lahaul, Spiti, and Kinnaur districts) and Jammu and Kashmir (Leh and Kargil districts). The region is one of the most elevated (2900 m to 5900 m asl) and coldest regions of the earth. Ladakh

Fig. 9.1 Apricot with lucerne

Table 9.2 Medicinal, aromatic plant and culinary herb species growing at different elevations in humid temperate region of India (Thakur et al. 2010)

S. no.	Crop/plant/herb	Botanical name	Altitude (feet[a])
	Crop species		
1	Shatavari	*Asparagus racemosus*	2500–5500
2	Chirayata	*Swertia chirayita*	5500–7000
3	Ashwagandha	*Withania somnifera*	2500–4500
4	Giloy	*Tinospora cordifolia*	2500–5000
5	Meethi Tulsi	*Stevia rebaudiana*	Up to 3000
	Plant species		
1	Reetha	*Sapindus mukorossi*	Up to 5000
2	Baheda	*Terminalia bellirica*	Up to 4000
3	Harar	*Terminalia chebula*	Up to 4000
4	Amla	*Emblica officinalis*	Up to 6000
	Culinary herb species		
1	Thyme	*Thymus vulgaris*	Up to 4000
2	Rosemary	*Rosmarinus officinalis*	Up to 4000
3	Oregano	*Origanum vulgare*	Up to 4500
4	Sweet marjoram	*Origanum majorana*	Up to 3000
5	Mint	*Mentha piperita*	Up to 3500

[a] 3.281 f = 1 m

Table 9.3 Fruit trees in agroforestry systems in central Himalayas

S.No.	Botanical name	English name	Local name	Family
1	*Citrus aurantiifolia*	Sour lime	Kagzi nimbu	Rutaceae
2	*Citrus pseudolimon*	Hill lemon	Pahari nimbu	Rutaceae
3	*Citrus sinensis*	Malta	Malta	Rutaceae
4	*Juglans regia*	Walnut	Akhrot	Juglandaceae
5	*Morus alba*	mulberry	Shatoot	Moraceae
6	*Prunus armeniaca*	Apricot	Khubani	Rosaceae
7	*Prunus persica*	Peach	Aaru	Rosaceae
8	*Punica granatum*	Pomegranate	Anar	Onagraceae
9	*Malus pumila*	Apple	Seb	Pumaceae

Fig. 9.2 General view of cold desert in Leh (Photo courtesy Pulkit Dagar)

covers more than 70,000 square km geographical area of Jammu and Kashmir, and Lahaul, Spiti, and Kinnaur cover 42% of total geographical area of Himachal Pradesh. The region is sparsely populated along the riverbanks of different valleys, namely, Indus, Nubra, Changthang, Zanskar, Suru valley, Lahaul, Spiti, and Kinnaur. The natural vegetation is very sparce and in pockets consisting of species of willows and poplars (Fig. 9.2).

The mean annual precipitation is less than 50 mm, received mostly in the form of snowfall. The region faces fast-blowing winds 40–60 km hr^{-1} mainly in the afternoon hours. The soil moisture remains frozen during long winters and low relative humidity during the summer months. The region has barren topography. The soils of the region are gravelly and sandy loams on the alluvial fans to sandy and slit clay

Fig. 9.3 Double-hump camel in Nubra valley (surviving mainly on sea buckthorn bushes and native forest trees)

loams on the Indus plains. Loose sandy loam texture, high percentage of stones and granules, low water holding capacity, high bulk density, and low soil fertility may be due to result of uneven distribution of plantation or sparse vegetation. The region has very short cropping season as the land remains landlocked for more than 6–7 months every year during extreme winter. Due to scattered small landholdings, local population subsists on limited crops and largely depends on natural resources for meeting diverse subsistence needs which has led to overexploitation (Singh 2010). However, main sources of income are rearing of Pashmina goat or Changthangi goat which provides cashmere wool for making well-known Pashmina shawl, ecotourism activities, and apricot and other temperate fruits (Singh and Dwivedi 1998). Double-hump camel in Nubra valley is a popular animal surviving on mainly sea buckthorn (*Hippophae rhamnoides*) and native forest trees (Fig. 9.3).

Natural wealth of the region is under various biotic (overharvesting, grazing, trampling, invasion of alien flora, etc.) and abiotic (prolonged extreme low temperature, natural calamities, habitat fragmentation and degradation through increasing human settlements, climate change, tourism activities – high influx of tourist and army vehicles which generate pollutants, huge unmanaged solid waste, damaging to flora while camping, adventurous activities, etc.) pressures causing high ecological imbalance in the region (Raina and Koul 2011). Due to long and severe winter, human population pressure is more than carrying capacity of the vegetation. It is a well-known fact that through development of agroforestry system, the pressure on natural resources can be substantially reduced.

Fig. 9.4 General view of cold desert of Leh region (Photo courtesy Pulkit Dagar)

Table 9.4 Agroforestry systems in cold arid region of India

S.no.	Agroforestry system	Forest trees	Fruit trees	Vegetables/others	Others
1	Boundary plantation	Poplar, willow	Apricot, apple	Peas, cole crops	Sea buckthorn
2	Windbreaks	Poplar, willow	Apricot, apple	Vegetables	Sea buckthorn
3	Horti-pastoral	–	Apricot, apple	–	Alfalfa
4	Horti-silviculture	Poplar, willow	Apricot, apple	Vegetables	–
5	Horti-silvopastoral	Poplar, willow	Apple, apricot	–	Alfalfa

A general view of the valley consisting of willows, poplars, and other vegetation is shown in Fig. 9.4. Willow species (*Salix fragilis* and *S. alba*) and poplar (*Populus nigra* and *P. alba*) are important tree elements of cold desert agroforestry systems in this region (Table 9.4).

Their ability to grow through 1 to 4 years shoot-cutting plantations under extreme and xeric climatic conditions of cold deserts makes them ecologically suited and socially accepted for forestry programs (Sharma and Sharma 2000).

Willow and poplar species in cold deserts do combat desertification and thrive well in these areas as compared to any other species. Small size of landholdings is one of the main constraints for establishing many willow and poplar plantations. Apart from these two plant species, *Elaeagnus angustifolia* (Tsersing) and *Robinia* are two other important plant species which are getting popularity in plantations in lower-altitude regions. These plants are easy to propagate by hardwood cuttings and

Fig. 9.5 Sea buckthorn with willow (in background)

seed, respectively, and grow faster than other species, even in poor and water-stressed conditions. These plants are primarily used for fodder, fuel, and shed, whereas poplar and willows are grown for its timber values.

Among fruit crops, apricot and apple are the two major crops grown in the region since time immemorial. These fruit crops are mostly grown in agroforestry system with forest species or with alfalfa fodder and even with vegetable crops and grain crop like wheat and barley. It is very difficult to get a pure commercial orchard of any fruit crop in these regions, without ago forestry. Apricot is well adopted to the region, and certain cultivars are unique and specific to these areas, which play important role in livelihood of the local farmers. The crop is very hardy and grows successfully in the regions below 3300 m msl even in rocky, poor, and water-deficient conditions. Apple is also grown in the similar agroforestry pattern and can be grown successfully up to 4000 m msl fields where even apricot fails to yield fruits (Dwivedi et al. 2007). Sea buckthorn (*brahmphal*) is a new emerging crop of the area, which is a multipurpose shrub covering vast areas naturally (Fig. 9.5), which by its nutraceutical and pharmaceutical storehouse both leaves and fruits and atmospheric nitrogen-fixing ability besides being excellent fuel and ideal plant to check wind and water soil erosion has become important crop for agroforestry in the region. There are huge sea buckthorn natural forests in cold desert of India.

To provide sustainable livelihood and environment security while maintaining present standard of living, there is a dire need of crop diversification in traditional agroforestry system. Keeping suitable tree species as well as horticultural crops in mind, the system should be modified into an integrated agroforestry system.

Combinations of agriculture, horticulture, silviculture, and pasture will help to increase productivity of available land resources without undermining ecology and environment sanctity. Increasing productivity will open new avenues of employment generation particularly through integration of rare herbs in farming and dairy and goat farming in the system. It is hoped that involvement of horticultural crops (fruits, vegetables, herbs, spices, grasses, and flowers) in agroforestry models throughout the region will help in social, economic, and environmental development of this cold desert.

*6.1 Sea Buckthorn/Brahmphal (***Hippophae rhamnoides***) - A Multipurpose Bush*

Sea buckthorn is a multipurpose (medicinal, biofuel, nitrogen fixing, fodder, and feed for double-hump camel and birds) thorny deciduous, dioecious shrub. Its leaves, flowers, and fruits are used for treating arthritis, gastrointestinal ulcers, gout, and skin and coronary heart diseases. Sea buckthorn leaves are used in making herbal tea as a source of vitamins, antioxidants, protein building blocks (amino acids), fatty acids, and minerals for improving blood pressure and lowering cholesterol, thus preventing and controlling blood vessel diseases and boosting immunity. Sea buckthorn berries are storehouse of nutrients and pharmaceuticals. The seed and berry oil has strong antioxidant activity and is used as an expectorant for loosening phlegm for treating asthma, heart disorders, and angina (Dwivedi et al. 2006). This plant finds special place in agroforestry of cold arid region (Fig. 9.6) and is used as bio-fence to crop fields (Fig. 9.7); checks wind and water soil erosion; provides fruits, fuel, and fodder; and sustains double-hump camel, birds, and other fauna. It is considered an excellent bio-fence plant on cold desert Indian boundaries with China and Pakistan. It is a potential agroforestry crop in Ladakh and similar terrain and climate.

7 Issues in Temperate Agroforestry

Although the issues in temperate agroforestry are site specific, in general some of main issues are enlisted here as:

(a) Though agroforestry policy in the country has been framed and approved, its implementation is awaited in temperate region.
(b) There is linkage gap between technology developers and stakeholders. Due to inadequate and not very effective agriculture extension services, there is low adoption of the developed technology at field level.
(c) Adequate research is needed to quantify the benefits of temperate agroforestry systems in terms of economic return and environment improvement.
(d) There is lack of proper/optimum combination of trees with crops which lead to the low productivity of the practiced systems.

Fig. 9.6 Sea buckthorn as agroforestry bush (grasses between two rows)

Fig. 9.7 Sea buckthorn used as fence around agricultural field

(e) There is need to address the spatiotemporal sequence of the different components in the agroforestry systems.

(f) Only limited forest tree species are grown in the existing systems of farming. Low diversity in the temperate region is due to climatic and geographical conditions. This is leading to very limited scope in selection of the different components of the agroforestry systems. Poplar and willow trees are the main trees inhabiting the area in cold desert region. Hence the technocrats are left with little choice. This is the major issue in the way of advancing the temperate agroforestry. Climate change is likely to open cultivation of new tree/plant species due to increase in temperature.

(g) Limited adoption of agroforestry systems due to smaller landholdings. Additional incentives on inputs like seeds, planting material etc.,on agro-forestry may boost adoption of the system in such regions.

Above issues are common in temperate agroforestry. In cold arid region, farmer faces other problems for adopting agroforestry. Among these problems, lack of proper irrigation facilities (84.31%) is the major negative factor faced by farmers. The other issues are lack of fencing, stray cattle menace, nonavailability of seedlings, and small landholdings which could be the major bottleneck in motivating the farming community to go for tree planting on their farmlands.

8 Conclusion

The role of agroforestry in meeting either present or future requirements of fuelwood, food, fodder, and small timber and for environmental protection has been very well recognized in temperate region of the country. The scarcity of fuelwood and fodder is widespread and is affecting seriously the living conditions in temperate region. An appropriate technology of tree integration with agriculture/horticulture is a welcome step in this region. Agroforestry scientists can synthesize site-specific technology, and administration should develop a suitable infrastructure for the disposal of diversified products from such a system.

The temperate agroforestry has certain issues like lack of proper area-specific policy regime, knowledge gaps of technical know-how of the existing systems, low yield of the existing systems, lack of efficient utilization of space and time, only few limited tree species that are grown, and low adoption of agroforestry systems. Farmers are reluctant to go for agroforestry practices due to small landholdings as per geographical features. Lack of irrigation facility is the major issue in the dry temperate region. There is linkage gap between technology developers and stake holders despite various agroforestry models developed by different research institution in the region.

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Chapter 10
Alley Cropping with Short Rotation Coppices in the Temperate Region: A Land-use Strategy for Optimizing Microclimate, Soil Organic Carbon and Ecosystem Service Provision of Agricultural Landscapes

Ansgar Quinkenstein, Penka Tsonkova, and Dirk Freese

Abstract Conventional agricultural practices have been associated with negative effects, such as reduction of soil fertility, pollution of surface and groundwater and loss of biodiversity and ecosystem services (ES). To mitigate these effects, while sustaining high levels of crop production, innovative land-use practices are necessary. A promising land-use approach are alley cropping systems (ACS) with short rotation coppices, which are agroforestry systems, that combine the cultivation of conventional agricultural crops with fast-growing trees to produce biomass for energy purposes at the same time on the same piece of land. In the presented study, the effects of trees planted in ACS on agricultural land in Central Europe on microclimate, on soil organic matter (SOM) and on the provision of ecosystem services (ES) were elaborated, based on a review of relevant literature and results of recent research projects. The outcomes suggest that, due to their structural complexity, ACS can be more efficient regarding main microclimatic factors than either crop or tree monocultural systems. As a main factor, wind protection by the hedgerows in ACS was identified. Other microclimatic factors, such as light, temperature or evaporation, were also clearly influenced by the presence of trees; however, occurring interactions were often complex, and cause-effect relations were difficult to ascertain. A further outcome is that planting trees on agricultural sites potentially increases soil organic carbon (SOC) stocks, which can be considered as a main indicator for soil humus and soil fertility. However, it became evident that, in addition to the depth dimension (30 cm sampling depth can be considered as insufficient), the dimension of time needs to be taken more strongly into account. The authors suggest a division of the lifetime of agricultural trees in an initial (SOC stocks may decrease), a transitional (stocks approach steady state; SOC distribution

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pattern in the soil may change) and a steady-state phase (no major changes in stocks or distribution patterns) when interpreting effects of trees on SOC. Subsequently, in the attempt to value the effects of ACS on crop productivity and soil, suitable and transferable methods for the assessment of ES were discussed. It was demonstrated that the provision of ES from ACS was higher than from conventional agriculture and that ACS can increase productivity while sustaining high levels of SOC. Summarizing, the results suggested that ACS – if designed and managed appropriately – may function as a practical and diverse tool to mitigate negative effects of agricultural production.

Keywords Agroforestry · Alley cropping system · Biomass production · Ecosystem services · Microclimate · Soil organic carbon

1 Introduction

Driven by the necessity to sustainably adapt agricultural production to changes in weather regimes and the growing demand for renewable energy carriers, new land-use systems and land-use strategies are put to the test. In this regard, the concept of agroforestry is gaining attraction in the temperate zone in recent years (Rigueiro-Rodríguez et al. 2009a).

A main characteristic of agroforestry systems is the large area share of trees which are combined with feedstock or agriculture on the same site (Nair 1985). The advantage of such mixed cropping compared to monocropping systems is the creation of a variety of interactions between the trees and the crops, comprising aspects of the nutrient and water cycle, microclimate and biodiversity (Nair 1993). Tree-induced interactions may sustainably stabilize or improve yield (Kort 1988) and mitigate negative effects of agricultural production on the environment, such as wind damage and soil erosion (Böhm et al. 2014), pollution or eutrophication of soil and waterbodies (Osborne and Kovacic 1993) or relative poverty of species (Greef et al. 2012). Furthermore, due to a more extensive management of agroforestry systems (at least of the areas with trees), the use of agrochemicals, such as fertilizer or pesticides, and soil cultivation measures are reduced. In result, agroforestry potentially produces ecological and economic benefits from which nature, society and land user may benefit (Dupraz et al. 2005; Quinkenstein et al. 2009a; Tsonkova et al. 2012). However, the intensity and the specific characteristics of these interactions depend mainly on the design and management of the system as well as the local site and growth conditions (Nair 1993).

In the temperate region, traditional agroforestry concepts, which focus mainly on food production and, therefore, on the optimization of nutrient and water cycles (Steppler and Nair 1987), are supplemented by complementary requirements such as production of woody biomass as energy resource, carbon (C) sequestration or provision of ecosystem services (Hall et al. 1991; Rigueiro-Rodríguez et al. 2009b; Kumar and Nair 2011). In this context, the agroforestry variant alley cropping with

Fig. 10.1 Alley cropping system for biomass production in Eastern Germany, looking north-south direction along tree rows of poplar and winter wheat in the alleys (Photo: Dirk Freese, 2014)

short rotation coppices (ACS) became relevant in Central Europe (Grünewald et al. 2007). ACS are agroforestry systems in which several sets of single or multiple rows of trees are planted in parallel tree strips with variable space between them (Nair 1985). This design creates alleys within which agricultural crops are cultivated using conventional techniques (Fig. 10.1).

Within ACS, fast-growing tree species such as poplar (*Populus* spp.), black locust (*Robinia pseudoacacia*) or willow (*Salix* spp.) are used. The trees are planted as cuttings or saplings in high densities of typically 8,000–15,000 (and more) plants per hectare wood area in single- or double-row design. This planting pattern facilitates quick growth and easy harvesting with specialized machinery, typically, at intervals of 2–6 years (Fig. 10.2).

The utilized tree species can resprout during the growing season following harvest, which allows such systems to be run for 20–30 years without replanting the trees, before yield starts to decline. The harvested wood is chipped directly at the field and, usually, used for power and heat production by combustion.

During the last years of ACS research, the influence of these agroforestry systems on microclimatic conditions (protection from erosion, moisture availability), soil humus contents (soil fertility, C sequestration) and the potential of agroforestry systems to sustainably provide ecosystem services (soil fertility, sustainability, system productivity) emerged as important ACS-related research issues (Grünewald et al. 2007; Quinkenstein et al. 2009a; Tsonkova et al. 2012).

The following text provides an overview of results of selected growth experiments in ACS systems in Central Europe. The focus is put on the influence of ACS on microclimate, the influence on soil organic matter (SOM) and the potential of ACS to provide selected ecosystem services (ES). Relevant scientific literature is reviewed and complemented with results from ongoing field studies.

Fig. 10.2 Top, mechanized planting of poplar cuttings in an ACS on agricultural land in Eastern Germany (Photo: Michael Kanzler, 2011); bottom, mechanized harvesting of short rotational black locust trees on a reclamation site of a lignite opencast mine in Eastern Germany (Photo: Ansgar Quinkenstein, 2011)

2 Microclimate

The agricultural hedgerow systems in ACS increase the complexity and structural diversity of agricultural landscapes and, thus, modify microclimatic conditions in the sheltered areas in several respects (Quinkenstein et al. 2009a). By means of appropriate species selection, design and management of the hedgerows, these effects can be optimized to favour agricultural crop production. Main microclimatic factors that may be influenced by ACS are wind speed, wind turbulences, light distribution (shading by the trees), temperature, precipitation distribution, evaporation/

evapotranspiration and available soil moisture (Quinkenstein et al. 2009a; Tsonkova et al. 2012). The intensity of these interacting microclimatic effects depends mainly on the height, length, structure and density of the hedgerow, the spatial layout of ACS (e.g. orientation of the hedgerows according to prevailing wind direction), the applied management (e.g. rotation interval and harvesting strategy) and the utilized tree species (Ringler et al. 1997; Brandle et al. 2004). The large number of different interactions can be summarized in two major potential microclimatic influences of ACS in temperate Europe: influences on the wind speed and influences on the water regime at the site (Tsonkova et al. 2012).

2.1 Wind Speed

If properly designed, ACS may function as an agricultural system consisting of multiple windbreaks, due to their composition of several hedgerows. Windbreaks provide shade and shelter for the crops and thus have been long used as a management technique to produce a more beneficial microclimate for agricultural crop production compared to open field (Cleugh 1998; Nuberg 1998). Such structures alter the mean wind speed, wind direction and turbulence of the airflow and provide shelter for some distance downwind with the positive effects that soil erosion by wind (Kort 1988) and the hazard of crop losses by physical damages due to strong winds are reduced (Cleugh 1998; Nuberg 1998). Accordingly, planting windbreaks is a common measure to prevent soil erosion by wind (Sudmeyer and Scott 2002; Brandle et al. 2004), especially at intensively cultivated areas with light erodible soils, such as can be found in Eastern Germany (Grimm et al. 2002; Nordstrom and Hotta 2004).

A typical wind profile around a single hedgerow can be divided into the ‘quiet zone’, a triangular zone that extends between three and eight times the height of the hedgerow leeward of the trees, and the ‘mixing zone’, a turbulent layer of air above and downwind of the ‘quite zone’, which merges into an ‘equilibrium’ zone in a leeward distance to the hedgerow of more than ten times the height of the hedgerow, where the original wind profile is re-established (Cleugh 1998). The extension and shape of these zones mainly depend on the width, height, structure and permeability or density of the hedgerow, as well as its continuity and spatial orientation (Brandle et al. 2004).

Reports of several studies regarding the effectiveness of windbreaks in wind reduction have been discussed. Sudmeyer and Scott (2002) reported that if the windbreak was perpendicular to the wind direction, wind speed reductions of greater than 20% occurred over the whole growing season for up to 3–6 tree heights from the windbreaks. Brandle et al. (2004) investigated different types of windbreaks (regarding composition and density) and reported extensions of the wind protection zone of up to 30 times the height of the windbreak leeward until the wind speed regained 100% of open-field wind speed. The authors reported also of small wind protection zones windward of the hedgerows of up to three times the height of the hedgerows (Brandle et al. 2004). Regarding ACS, Böhm et al. (2014) investigated the wind speeds in two ACS in Brandenburg, Germany, over a period of 5 years (including a partial harvest of the trees) and 1 year, respectively. The authors reported that the wind speed in crop alleys was reduced significantly within the ACS. In the middle of 24-m-wide crop alleys, the measured decrease of the annual average wind speed was more than 50% compared to the wind speeds at open field (Böhm et al. 2014). The authors concluded that ACS can represent effective windbreaks despite their comparably low hedgerows compared to 'conventional windbreaks' consisting of multiple rows of trees and/or shrubs of different heights (Böhm et al. 2014).

2.2 *Water Regime*

The water regime in ACS is influenced by a variety of microclimatic factors, and thus the water availability in the system usually depends on a complex interaction of different processes. Key processes for the water regime in ACS are distribution of precipitation, radiation, temperature, evaporation and evapotranspiration and influences of the plants on available soil moisture.

2.2.1 Distribution of Precipitation

Do to their windbreak properties, hedgerows in ACS may alter the distribution of precipitation within ACS compared to open-field conditions (Brandle et al. 2004). Typically, depending on the height and the porosity of the hedgerow, the precipitation increases slightly in the area immediately adjacent to the hedgerow on both sides. A small reduction in rain may occur on the downwind side due to wind turbulences and interception losses due to the trees and on the upwind site as the hedgerow may function as a barrier that redirects the airflow over the hedgerow (Monteith et al. 1991; Brandle et al. 2004; Kanzler and Böhm 2015). Due to the rain interception by the trees, slightly higher soil moisture values may be measured under the trees due to increased stem flow or dripping from the canopy (Monteith et al. 1991; Brandle et al. 2004). In addition to that, during the winter season, hedgerows lead to a more equal distribution of snow and to a delayed melting of snow during the spring that can help to enlarge water resources of the soil throughout the year (Scholten 1988).

2.2.2 Temperature and Radiation

Lower wind velocities on the leeward side of ACS hedgerows lead to a reduction in turbulent mixing of air masses with different temperatures compared to the conditions on open field. In result, in the wind protection zone of the hedgerows, the air temperature may be several degrees higher than in the open field (Brandle et al. 2004). An opposite effect results from the shading by the trees, which is an additional influencing factor for the microclimatic conditions in ACS. Generally, shading reduces the available radiation for the plants which leads to a reduction of photosynthesis activity. Furthermore, average air temperature as well as temperature extremes is reduced, which leads to a reduction of heat-induced plant damages, as well as reduces rates of transpiration and water evaporation from the soils, at least near the hedgerows (Feldhake 2001; Brandle et al. 2004). On grassland, in addition to an increase of agricultural production, this effect may also be useful to provide shade-, rain- and water-shading zones for feedstock. However, due to the relatively low trees in ACS (depending on the rotation interval up to about 5–6 m) and wide crop alleys (depending on the system design), the effect of shading is smaller than in types of agroforestry systems in which the trees can develop large, overhanging canopies.

The described microclimatic relations regarding temperature and radiation are supported by results published by Kanzler and Böhm (2015). The authors investigated microclimatic effects in an ACS with poplar and black locust hedgerows managed in short rotations and crop alley widths of 24, 48 and 96 m, established in 2011 on a former agricultural site in Brandenburg, Germany, and in an ACS with black locust established in 2007 on a lignite-mining reclamation site, about 35 km distance to the first site. They reported for the two investigated ACS slightly lower temperatures (about 1% lower) in the ACS on the agricultural site but about 5% lower temperatures for the ACS on the reclamation site. However, they found a clear reduction of extreme temperatures in both ACS compared to the reference sites (Kanzler and Böhm 2015). At the same time, the authors report a reduction of solar radiation of about 11% in vicinity to the hedgerows (about 3 m distance), but they stress that no direct effect on crop yield could be identified (Kanzler and Böhm 2015).

2.2.3 Evaporation, Evapotranspiration and Air Humidity

A reduction of wind speed and of wind turbulences by tree rows is an important influencing factor on the evapotranspiration rates within ACS, what might be a relevant feature of agricultural trees especially in dryer regions (Blenk 1953). Air turbulences are a main mechanism for exchanging heat and water vapour between land surface and atmosphere and are more effective in the direction from the surface to the atmosphere (Cleugh 1998). Accordingly, temperature and air humidity in the 'mixing zone', according to Cleugh (1998), may be lower by day but higher by night than in the 'quiet zone', whereas evaporation shows the opposite behaviour (McNaughton 1988; Cleugh 1998). However, these cause-effect relationships are not always clearly identifiable, because growing plants may adapt to the microclimatic conditions in the different zones, e.g. by modifying stomatal conductivity or leaf sizes, by what the evapotranspiration near the hedgerows might even increase (Brenner 1991). Kanzler and Böhm (2015) reported for the investigated ACS on agricultural area (see above) an average 3% higher air humidity about 3 m leeward of the hedgerow and about 1% higher humidity in the middle of a 96-m-wide crop alley compared to a reference site. However, for the ACS in the mining reclamation area, they reported the opposite trend with lower air humidity within the ACS compared to the reference site at an open field (Kanzler and Böhm 2015).

2.2.4 Soil Moisture and Groundwater Recharge

Plant-available soil water is one of the key factors for agricultural crop production. Generally, soil water depends on climatic conditions (e.g. precipitation), soil properties (e.g. texture or humus content) and management factors (e.g. ploughing) but is also influenced by the microclimatic interactions outlined above. Due to higher transpiration rates of the trees compared to agricultural crops throughout the year (Quinkenstein et al. 2009b), usually, lower soil moisture values directly under the trees than under the crops are measured. Accordingly, Kanzler and Böhm (2015) reported for the investigated ACS on the reclamation site and for the ACS on agricultural land in average lower soil moisture values in the topsoil (0–20 cm) than for the reference sites. However, for the ACS on the agricultural site, they reported an average 6% higher soil moisture in 20 cm soil depth on the downwind side of the hedgerow compared to the reference site. They explained this finding with a possibly higher dew formation due to the trees in the ACS, which is located close to a river, but stated also that the high variability of soil texture at the plot could have influenced the measurement results (Kanzler and Böhm 2015). Similar results were reported for an experimental ACS with poplar, willow and black locust trees on reclamation areas of the lignite-mining pit ‘Jänschwalde’ in the same region. The authors reported that the soil moisture from 0 to 30 cm soil depth in the middle of the 18-m-wide field strips was about 3–5% higher than on a neighbouring conventional agricultural reference site (Quinkenstein et al. 2009b).

Controversially discussed is a possible influence of agricultural trees on the recharge capacity of agricultural landscapes on groundwater, which is – at least in densely populated areas like Germany – an important and potentially scarce resource for drinking water. Within a modelling study, Quinkenstein et al. (2009b) investigated the average annual groundwater recharge, considering several water regime parameters such as interception or evapotranspiration, under poplar and black locust short rotation stands for different weather regimes and site conditions, typical for Eastern Germany, and compared the results with recharge rates under conventional agricultural crops. In result, the authors reported highest seepage rates of 35–39% of the precipitation in open area for the agricultural crops and clearly lower seepage rates of 17–20% and 11–14% for black locust and poplar, respectively (Quinkenstein et al. 2009b). Although the modelled seepage rates may be subject to some restrictions (see Quinkenstein et al. (2009b) for details), considering ACS, the seepage rates can be expected to be more similar to the rates under agricultural crops due to the comparably smaller area shares of trees.

3 Soil Organic Matter (SOM)

3.1 Functions and Importance of SOM for Soil Fertility

Soil organic matter (SOM) is defined as the sum of all biologically derived organic material in the soil or on the soil surface excluding aboveground living plant parts (Baldock and Nelson 1999). Since the direct determination of SOM contents is methodically difficult, most scientific studies measure organic C (C_{org}) contents and apply, if necessary, conversion factors ranging from 1.72 to 2.0 to the results to obtain SOM contents (Baldock and Nelson 1999). These conversion factors are variable, because they depend mainly on the C content of dead organic matter which ranges around about 50% but varies in dependence of the composition of the organic material and increases with increasing grade of humification (Kuntze et al. 1994). To avoid these variances in most cases, only the C_{org} or, in relation to the soil, the soil organic carbon (SOC) contents are given.

SOM describes a very complex mixture of different organic compounds. According to Kuntze et al. (1994), the main fractions of SOM are dead organic material (about 85%), plant roots (about 10%) and edaphic biomass (about 5%) which, in turn, consist of a large variety of different chemical and biological components. Due to this chemical complexity, SOM interacts in various ways with soil processes and influences soil properties, which have been broadly divided into biological/biochemical, chemical and physical aspects (Baldock and Nelson 1999). The first group comprises the provision of organic energy sources for biochemical soil processes by SOM and its role as a source of macro- (N, P and S) and micronutrients as well as a large variety of different organic substances, influencing pools of plant-available nutrients in different ways (Baldock and Nelson 1999). Furthermore, sufficient quantities of SOM (stabilized in terms of quantity and quality) and associated nutrients can enhance the resilience of ecosystem against external stresses (e.g. functioning as buffers for in-excess nutrients) and sustain a healthy soil life and plant growth. Regarding chemical soil properties, SOM is an important sorbent for inorganic and organic substances in the soil solution due to a large reactive surface and a high and partly pH-depending charge capacity of the organic soil compounds (Blume et al. 2016). Therefore, SOM is an important controlling factor for the cation exchange capacity of soils and may enhance retention of important soil ions such as K^+, Ca^{2+}, Mg^{2+}, NH_4^+ or NO_3^-. These chemical properties of SOM also lead to a comparably high buffer capacity of SOM against acids and, therefore, support a sustainably stable soil pH (Baldock and Nelson 1999). Moreover, SOM alters the biodegradability activity and persistence of pesticides in soils and may mitigate the effect of toxic metals, as well as enhance the availability of important nutrients such as phosphorus due to chelation of ions (Baldock and Nelson 1999). Regarding physical properties, SOM stabilizes soil structure through formation of stable aggregates by creation of organo-mineral compounds. Due to its influence on soil structure and pore geometry (Baldock and Nelson 1999), its charge and the presence of hydrophobic and hydrophilic areas, SOM is an important determinant for the water storage capacity of soils – it can absorb up to 20 times its mass of water (Baldock and Nelson 1999). Because of these factors combined, SOM enhances the resilience of soil particles against erosion and reduces leaching processes, and due to its dark colour, it also influences soil temperature regime to a certain extent (Baldock and Nelson 1999; Blume et al. 2016). Summing up, SOM usually accounts only for a small proportion of soil mass but, nevertheless, is of special relevance regarding soil fertility and, as the globally most important storage form of biologically sequestered C, also of high relevance regarding the global C cycle. Cultivation strategies greatly influence SOM as plants and their residues are the main source of SOC.

3.2 Formation, Decay and Composition of SOM

The major source for C_{org} in natural systems is the vegetation. During photosynthesis, the plants assimilate C from atmospheric carbon dioxide (CO_2) and use it to build up organic compounds. A certain proportion of this fixed C is respired directly by the plants (autotrophic respiration). The remaining C compounds are incorporated in the living biomass and, with time, gradually transferred as aboveground or belowground litter, as exudates or in other forms to the litter layer or directly into the soil. There, dead organic biomass is decomposed and mineralized by the edaphon, the fixed C is respired (heterotrophic respiration) and released back to the atmosphere as CO_2. The contained nutrients are released to the soil solution from where they can be recaptured by organisms and incorporated into living biomass again (Blume et al. 2016). The total amount of SOM in the soil is the result of a dynamic equilibrium between deposition rate of organic residues and the mineralization rate, which in turn depends on the microbial activity (Sollins et al. 1996; Post and Kwon 2000). Important factors supporting an increase of C_{org} accumulation in the soil are large amounts of organic input of sufficient quality, the relocation of organic materials into the deeper soils by direct input (roots) or bioturbation by soil organisms and decomposition conditions that favour the development of stable C compounds. The activity of soil microbes, which, usually, is highest in the topsoil, is mainly controlled by weather conditions (temperature, moisture), nutrient supply and level of soil aggregation, which influences the physical availability of organic material, water and air to the microbes (Schinner and Sonnleitner 1996; Sollins et al. 1996). Major factors that favour the formation of bigger and more stable soil aggregates are plant remnants, root exudates and soil fungi (Blume et al. 2016). In this regard, the formation of organo-mineral compounds in the intestines of earthworms is of special relevance, due to the large resilience of organo-mineral complexes against biological, chemical or physical degradation (Post and Kwon 2000; Blume et al. 2016). Furthermore, the SOM content of soils is usually closely related to soil texture (especially the clay content) and, therefore, is also depending on abiotic site conditions (Schimel et al. 1985). Generally, soils with finer textures can store more C_{org} than soils with coarser textures (Blume et al. 2016).

The highest concentrations of C_{org} are found in the litter layers and in the topsoil. Litter horizons have an organic proportion of up to 100%, and their C_{org} contents usually range from 40% to 45% (Blume et al. 2016), whereas higher values of up to 55% C_{org} in the litter layers of forest soils in Central Europe have also been reported (Zech et al. 1992). Typical contents of C_{org} in agricultural soils in Central Europe range between 1% and 2% and in forest soils between 0.5% and 10% (Wessolek et al. 2008). Accordingly, C_{org} contents of 0.75–2% for Ah horizons of forest and agricultural soils have been reported, while in grassland higher values of up to 15% can be found (Blume et al. 2016). In contrast, the lower soil horizons of most soil types show clearly lower C_{org} values of 0.1–1% (Blume et al. 2016). The total stocks of organic matter stored in German arable soils in the topsoil layer were estimated to range between 100 and 200 Mg ha^{-1} (Blume et al. 2016).

3.3 Influence of ACS on SOM

The formation and maintenance of site-related high quantities of SOM are of great importance for the development and conservation of the soil fertility of agricultural soils. Agroforestry systems integrate tree with crop and animal production systems and are management practices that conserve and potentially enlarge C_{org} stocks in the biomass and the soils more than pastures or agricultural crops (Schroeder 1993). This idea assumes that integrated multispecies systems are more efficient in their resource usage (space, nutrients, light, water), produce beneficial interactions which stimulate plant growth and provide larger amounts of aboveground and belowground litter and favourable conditions for soil life, decomposition and humus formation than mono-species systems (Nair et al. 2009; Tsonkova et al. 2012). An important controlling factor seems to be the reduction of soil cultivation activities under the trees due to the limited accessibility of the forested areas (e.g. only possible after removal of the trees), by which the period of soil rest is enlarged (Rehbein et al. 2013). This, in combination with modifications of microclimatic conditions (e.g. alterations of moisture and temperature) and the comparably large litter production by the trees, leading to the formation of a persistent litter layer, protects the soil from microclimatic stress factors, stimulates the formation of more stable macroaggregates and reduces turnover and losses of C_{org} (Quinkenstein et al. 2009a, 2017; Rehbein et al. 2013).

3.3.1 Litter Production of Agricultural Trees

The annually produced litter biomass, as important raw material for SOC formation, depends in quantity and quality on the land-use system design and management (planting density, rotation interval, fertilization), the cultivated species (trees to produce biomass or high-value timber) as well as local growth conditions (weather, soil properties). Over a longer period, the trees in ACS develop a larger root system and more aboveground biomass, producing larger amounts of litter than annual agricultural crops, and, similarly important, enable the formation of a persistent litter layer. Generally, deciduous trees produce more organic material for SOM formation than coniferous trees, which produce more material than grassland, which, in turn, produce more material than agricultural areas (Kuntze et al. 1994).

Schroeder (1993) conducted a literature review and estimated the average C_{org} storage in the aboveground biomass by agroforestry practices to be about 63 Mg C ha^{-1} (about 3.9 Mg C ha^{-1} $year^{-1}$) in the temperate ecoregions assuming a cutting cycle for the trees of 30 years. Because the shoot biomass produced by fast-growing tree species cultivated in European ACS typically is removed from the site every 4–7 years, it is usually not available for SOM formation. For these systems, a directly measurable biomass input into the soil is the mass of leaf litter and litter layer. An investigation of 18 sites, distributed all over Germany, with 2-year-old clones of poplar and willow resulted in an average produced dry matter (DM) leaf biomass of about 2.5 Mg DM ha^{-1} (Heyn et al. 2011). For 3- and 4-year-old poplar and black locust trees in an ACS on an agricultural site in Eastern Germany, a comparable annual leaf fall of about 2.5 Mg DM ha^{-1} was measured (Mirck et al. 2015). For the same site, with 4- and 5-year-old trees, a litter layer with a dry matter mass of about 4.7 and 5 Mg DM ha^{-1} on the forested area was measured 1 year later (Kanzler and Böhm 2015). Petzold et al. (2010) investigated the aboveground and belowground biomass of a 10-year-old poplar plantation in Saxony (Eastern Germany) and reported values of about 4.46 Mg DM ha^{-1} for leaf biomass and about 0.43 Mg DM ha^{-1} litter consisting of twigs and branches.

For the dryer conditions on a reclamation site of an opencast lignite mine in the same region of Germany, a higher litter accumulation and a litter layer mass of up to 11 Mg DM ha^{-1} in an 8-year-old ACS with black locust were reported (Kanzler and Böhm 2015). As opposed to aboveground biomass, leaf fall and litter layer mass of agricultural trees, the belowground biomass and its turnover are comparably hard to quantify. Ślązak et al. (2013) investigated the root biomass under different land-use systems and estimated with 3–4 Mg DM ha^{-1} higher biomass stocks under 4-year-old poplar plantations in Germany than under neighbouring willow plantations, fallow land or grassland. For a 10-year-old poplar site in Saxony, Petzold et al. (2010) reported a belowground coarse root biomass of about 32.6 Mg DM ha^{-1}, and Quinkenstein et al. (2012) measured a C_{org} stock in the living fine root biomass of between 0.25 and 1.51 Mg C ha^{-1} and in the coarse root biomass of between 0.48 and 11.51 Mg C ha^{-1} for 1- to 12-year-old black locust stands on reclamation sites in Eastern Germany.

The amount of organic material of the accumulated biomass in the aboveground or belowground plant parts or in the litter layer that is actually transferred to the SOC per time step depends on several factors (e.g. quantity, quality of the litter and edaphic activity) and is usually expressed in a turnover rate for the considered C_{org} fraction. These values are difficult to quantify, are highly variable and, therefore, often must be estimated (Quinkenstein and Jochheim 2015). For many applications, it is, however, more straightforward to measure the changes of SOC stocks directly.

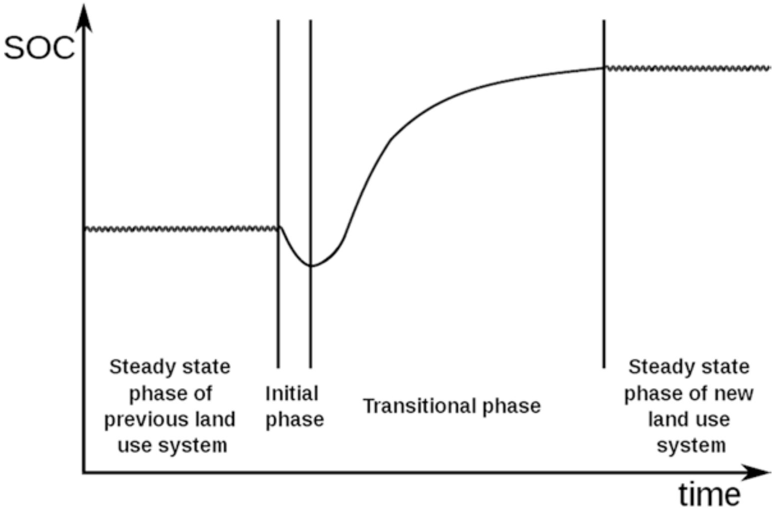


Fig. 10.3 Hypothetical influence of the establishment of trees on agricultural areas on the SOC stock with highlighted initial, transitional and steady-state phase, whereas a higher biomass productivity of the trees after the initial phase compared to the agricultural system is assumed

3.3.2 Soil Organic Carbon in ACS

Many studies give evidence that the establishment of agroforestry trees in agricultural areas enhances the C_{org} accumulation in the soils. However, published values of the estimated C_{org} sequestration potentials of agroforestry systems (in the biomass as well as in the soils) vary substantially, due to differences in scope, in methodology (e.g. sampled soil depth) as well as in assessment strategy (Nair 2011). To make the results better comparable, the effect of establishment of trees within ACS on the SOC stocks can be broadly divided into three stages which overlap under natural conditions: initial phase, transitional phase and steady-state phase (Fig. 10.3).

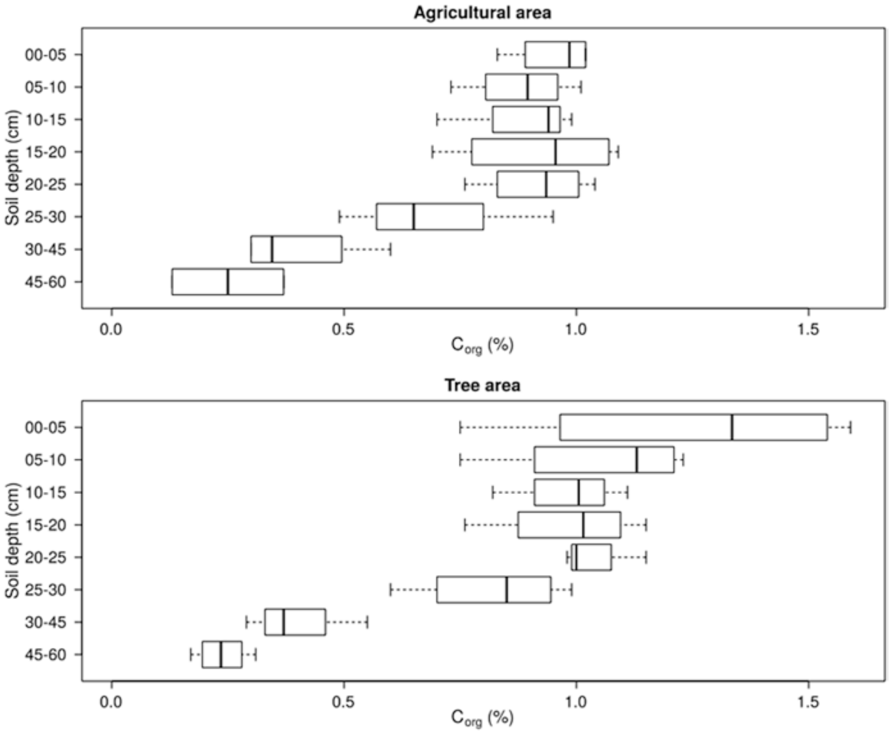
3.3.2.1 Initial Phase

A change of a land-use system (e.g. from conventional agriculture to ACS) always represents in the first place a disturbance of existing soil processes. Because of increased decomposition losses due to removal of the old vegetation and/or soil cultivation measures prior to tree planting, the soil might even initially lose C_{org} throughout the first 1–5 years, when the growth of the newly planted trees remains comparably low, depending on the biomass productivity of the newly established land-use system (Tsonkova et al. 2012). Regarding agricultural trees, this effect was described by Walle (2007) who investigated birch and poplar plantations in Belgium and found a C_{org} decrease of about 42% in a soil depth of 0–30 cm after 4 years of growth, compared to the amount of C_{org} present in the soil before planting the trees. Stetter and Makeschin (1997) investigated two sites in Germany with afforestations of poplar and willow and reported a slight decrease of SOC stocks during the initial phase. Similarly, Paul et al. (2002), who conducted an extensive review on SOC changes in the topsoil (up to 30 cm depth) after forest afforestation for more than 200 globally distributed sites, concluded that SOC decreased during the first 5 years of tree growth but then started to increase, so that after about 30 years, there was little difference or slightly more SOC than was present in the agricultural soil before afforestation. The initial decrease in total C_{org} stocks might, therefore, be related with a smaller biomass production of the young trees during the first years compared to conventional crops, while at the same time, the decomposition losses for the first years remain large (Paul et al. 2002).

3.3.2.2 Transitional Phase

When the planted trees start to develop, the produced biomass and, therefore, the litter available for decomposition and humification processes in the soil increases for a period of several years. Moreover, in the tree rows, no ploughing takes place, which, typically, produces more or less homogeneous soil conditions and C_{org} contents under agricultural management throughout the ploughing horizon from about 0 to 30 cm. Because of enhanced mineralization of C_{org}, which mainly affects easily decomposable litter residues in the formerly ploughed horizons (Jug et al. 1999), and leaching losses originating from system establishment activities, a change in the distribution of C_{org} within the soil profile occurs. This leads to the formation of a depth gradient with higher C_{org} values in the uppermost and lower values in the deeper soil layers compared to the more homogeneously distributed C_{org} in agriculturally managed soils. The investigation of the soil depth distribution of C_{org} in a 6-year-old ACS established on an agricultural site in Eastern Germany demonstrated this change in SOC distribution induced by agricultural trees (Quinkenstein et al. 2017). Soil samples were taken in the middle of 48-m-wide crop alleys and in the middle of the framing 11-m-wide tree strips, consisting of four rows of poplar trees. The results for the C_{org} contents showed usual average values for agricultural sites within that region but also a trend of higher values in the topsoil and lower values in the deeper soil layers (Fig. 10.4).

The C_{org} contents over all plots ranged from 1.10 ± 0.28 ($n = 8$), in the uppermost soil layer (0–5 cm), to 0.24 ± 0.08 ($n = 6$) in the lowest soil layer (45–60 cm). Comparing the tree with the crop plots, differences between tree and crop plots for specific soil depths were not significant; however, the results indicated that under the trees, the decrease of C_{org} with soil depth was significant ($p \leq 0.05$) – comparing the 0–5 cm and the 45–60 cm layer – and, as such, was more pronounced than in the soils under agricultural areas for which no significant difference was found for the same soil layers. The visual comparison of tree and crop plots (Fig. 10.4) supports this finding and reveals a trend of higher values in the topsoil under trees compared


Agricultural area

Tree area

Fig. 10.4 Average soil contents of C_{org} (n = 3–4) in the middle of the agricultural site (above) and the tree strips (below) of a 6-year-old ACS in Eastern Germany (n = 3–4; black bars: median; boxes: lower and upper quartile; whisker: distribution maximum and minimum; points: outliers; Quinkenstein et al. 2017, modified)

to the crop plots. Overall, the results indicated that the introduction of trees in the form of ACS into agricultural areas might initiate a change in the depth distribution gradient in soil regarding contents of C_{org} (Quinkenstein et al. 2017). A similar change of SOC distribution because of the planting of trees on agricultural lands was reported by Jug et al. (1999) who investigated changes in soil properties after afforestation of former agricultural and grassland areas with poplar and willow on three German sites. After a growing period of 7 and 10 years, respectively, they measured an increase of soil C_{org} in a depth of 0–10 cm, while a slight decrease of C_{org} for a soil depth between 10 and 30 cm occurred (Jug et al. 1999). Similar findings were reported for an afforestation of former agricultural areas with poplar and willow in Germany (Stetter and Makeschin 1997). The authors reported a slight increase of C_{org} in the uppermost and a slight decrease in the lowest investigated soil layer after 10 years of growth (Stetter and Makeschin 1997).

3.3.2.3 Steady-State Phase

Only when the C_{org} accumulation in the newly established land-use system surpasses the C_{org} loss via decomposition, additional C_{org} will be sequestered within the system (Schulze 2006), resulting in a higher steady-state SOC stock compared to the previous system. If ACS are established on agricultural land, a stable or increasing SOC content over longer time periods was reported by several studies. An investigation of the C_{org} contents from 0 to 30 cm in the soils under an ACS on an agricultural field (5-year-old at sampling) and an ACS on reclamation sites of a lignite opencast mining area in Eastern Germany (8-year-old at sampling) resulted in no significant changes in total C_{org} stocks for the first site, but a significant increase of about 1.48 Mg C ha^{-1} $year^{-1}$ under the trees (compared to an increase of 0.68 Mg C ha^{-1} $year^{-1}$ for the neighbouring agricultural areas) for the second site (Quinkenstein and Kanzler 2018). Medinski et al. (2014) compared agricultural areas with tree areas in three German ACS (between 1 and 4 years old) and reported in a soil depth of 0–3 cm a significant increase of C_{org} under the trees since planting.

If ACS are established on mining reclamation sites (with initially nearly no C_{org} in the soils), the C sequestration by the trees becomes even more evident and was pronounced also in deeper soil layers. Quinkenstein et al. (2011) investigated the SOC accumulation under four tree plantations of black locust established on lignite-mine reclamation areas in the Lusatian area in Eastern Germany, to a soil depth of up to 60 cm and time periods between 2 and 14 years of growth. The authors reported total C_{org} stocks of up to 106 Mg C ha^{-1} for the 14-year-old plantation and estimated an average accumulation rate of about 7 Mg C ha^{-1} $year^{-1}$ for the considered soil depth following a pseudo-chronosequence approach. Furthermore, Nii-Annang et al. (2009) investigated an ACS established in another reclamation area in the same region and reported lower C accumulation rates in the topsoil (0–30 cm). The authors estimated a C_{org} accumulation of 3.4 mg C m^{-2} after 9 years of black locust cultivation, which corresponds to an annual accumulation rate of about 1.85 Mg C ha^{-1} $year^{-1}$.

It is arguable whether the cited studies represent steady-state conditions within the considered ACS or if a steady state under agricultural conditions exists at all. Typically, for sites exposed to a constant land-use practice, time periods of up to 30–50 years are given until steady-state conditions for the C_{org} stock are reached (Robert 2001); however, even longer periods of more than 80+ years were reported (Jenkinson 1971). Due to the relative novelty of ACS, long-term studies on the development of SOC stocks are rare. Long-term studies from afforestations with forest trees could help to develop an idea of how the future development of SOC under ACS might look like. In general, from such studies, similar results were reported. For seven agricultural plots converted to tree plantations, Garten (2002) reported that SOC levels increased by 0.4–1.7 Mg C_{org} ha^{-1} (0–40 cm depth) within 10 years of establishment. Bambrick et al. (2010) investigated a 4-, an 8- and a 21-year-old tree-based intercropping site in Canada and found 77% and 21% higher SOC contents in 0–30 cm soil depth under the 8- and the 21-year-old trees, respectively, compared to nearby conventional agroecosystems, but no differences were detected at the youngest site. Post and Kwon (2000) conducted a comprehensive review of several studies on SOC sequestration after afforestation of agricultural sites and reported average values of 33.8 g C m^{-2} y^{-1} even after up to 250+ years since conversion.

Against this background, it needs to be considered that the average expected lifetime of ACS trees is only 20–30 years what (very likely) prevents that under the trees SOC-equilibrium is reached. However, if the whole ACS system is considered (including a ‘spatial rotation’ of tree strips), nearly steady-state conditions appear possible after an appropriate amount of time. In addition, a major issue, which makes the comparison of results of different studies regarding SOC challenging, is sampling depth. Most soil studies on agricultural sites are limited to the ‘ploughing horizon’, about 20–30 cm soil depth. Regarding tree-based systems such as ACS, this sampling depth can be considered as not sufficient, mostly, because tree roots in many cases extend to deeper soil horizons (see below). However, this issue has already been stated before (Nair 2011).

4 General Competition Effects

In agroforestry systems competition for resources such as light, water, space, nutrients between the trees and the adjacent crops is in many cases inevitable and needs to be managed to optimize the system’s output (Monteith et al. 1991). Studies have shown that yields close to agricultural trees may be reduced due to allelopathy (Singh et al. 1998), nutrient deficiency, shading, temperature effects or soil moisture deficiency (Kort 1988; Jose et al. 2000a). The degree of competition varies with the utilized species, system structure, management, general system location and soil and climate conditions. In ACS, the frequent cutting of the trees ensures that the trees usually don’t excess median heights of about 5–6 m (see above) and, accordingly, don’t develop large canopies. For this reason, competition effects are limited to the immediate vicinity to the trees, and aboveground competition factors (e.g. light access) might be less important than belowground factors such as competition for nutrients or moisture (Jose et al. 2000a, b). In this context, the lateral distribution of the roots is typically more important than the vertical distribution, whereas the development of a vertical stratified root system with the roots of annual crops in the upper and persisting roots of the trees in the lower soil layers is advantageous (Schroth 1998).

Many plants naturally tend to evade competition in the rooting zone by developing separate rooting systems (Schroth 1998). In the temperate region, the maximum rooting depth of annual crops usually ranges up to a few metres, whereas for the fast-growing tree species black locust (*Robinia pseudoacacia*), poplar (*Populus* spp.) and willow (*Salix* spp.), rooting depths of >7.9, >3 and 4 m, respectively, were reported (Stone and Kalisz 1991). The maximal root system diameters were of 14.0, 30.5 and 40.0 m for trees of different ages (Stone and Kalisz 1991). Accordingly, investigations in agroforestry systems in Nebraska (USA) with apple trees (*Malus* sp.) and corn (*Zea mays*) showed that the roots of the apple trees grew up to 2 m deep into the soil before they started to spread out laterally to evade water competition with the roots of the corn plants growing in the upper soil layers (Yocum 1937).

It might be possible to support the formation of layered root systems and reduce root competition to some degree by cultivating species that tend to develop vertically stratified root systems (Young 1990) or by cultivating crops with compact root systems able to deflect tree roots into greater depths (Schroth 1995, 1998). Regular harvesting, pruning or cutting lateral tree roots extending into the crop field by, for example, repeated ploughing can force the trees to relocate major parts of their root system into the deeper soil layers (Schroth 1998). However, the effectiveness of such measures depends on the system design (e.g. planting density) and species characteristics (Schroth 1998; Hou et al. 2003).

5 Productivity of ACS

All the factors mentioned above (microclimate, SOM, competition) influence the wood and crop production potential of ACS to varying degrees. In addition, it depends on many factors such as system design, which is characterized by the utilized tree species, average tree height, strip width and planting density; management regime, which is characterized by planting and harvest technology, rotation length, fertilization, quality of pest and weed control; and other general site and growing conditions such as soil water and nutrient availability (Quinkenstein et al. 2009a; Tsonkova et al. 2012). While the crops in ACS, typically, are managed conventionally (including periodical fertilizer or pesticide application), the trees are managed extensively (e.g. fertilization and pesticide application are reduced because (a) the area is not accessible to machines for several years and (b) lower application rates are sufficient for most tree species), and their development is more strongly dependent on natural growing conditions.

Fast-growing tree species typically cultivated in Central European ACS, such as poplar, willow or black locust, produce a harvestable shoot biomass in dry matter (DM) between 8 and 14 Mg DM ha^{-1} $year^{-1}$ (Lindroth and Båth 1999; Mitchell et al. 1999) on fertile agricultural sites. For tree plantations on average fertile soils in Eastern Germany, growth increments of about 6 and 12 Mg DM ha^{-1} $year^{-1}$ for willow and poplar have been reported (Scholz et al. 2004; Bemmann et al. 2007). In Northern Poland, even higher growth rates for a selection of willow of between 14.2 and 21.7 Mg DM ha^{-1} $year^{-1}$ were measured (Szczukowski et al. 2002), and Aylott et al. (2008) reported values for different poplar and willow clones of about 4.9–10.7 Mg DM ha^{-1} $year^{-1}$ using data from a 49-site short rotation coppice (SRC) yield trial network in the UK. Lower growth values were reported for more nutrient-poor soils under dryer conditions such as can be found in the opencast lignite-mining region of Lower Lusatia in Germany. Accordingly, for plantations on reclamation sites within that region and for different rotation intervals, average growth increments of 0.5–2.9 Mg DM ha^{-1} $year^{-1}$ for willow, 2.6–4.0 Mg DM ha^{-1} $year^{-1}$ for poplar and 3.1–9.5 Mg DM ha^{-1} $year^{-1}$ for black locust were reported (Bungart and Hüttl 2004; Grünewald et al. 2007, 2009; Quinkenstein et al. 2012).

Compared to either crop or tree monocultures, ACS are structurally and functionally more complex and, when properly managed, more efficient regarding major growing factors such as light, water or nutrients (Buck et al. 1999; Tsonkova et al. 2012). In addition, the introduction of trees into the agricultural area enhances the C sequestration potential of a landscape and, therefore, potentially increases humus stocks in the soil (Nair et al. 2009). Many studies show that the wind protection within windbreak systems has positive effects on crop yield over a range of climate and soil conditions (Baldwin 1988; Norton 1988). Typically, crop yields decrease near the hedgerows due to competition effects but increase in a zone further away from the hedgerows (Kowalchuk and de Jong 1995). Nuberg (1998) conducted a literature review on articles on windbreak effects on crop yields and reported for many different studies from all over the world that yield increases of up to 50% due to windbreaks compared to reference sites. Similar increases and top values of up to 70% more yield in systems with windbreaks compared to reference sites were reported in the review by Kort (1988). However, to what degree the crop production might benefit from wind protection effects depends on the specific characteristics of the considered system and the management. For example, harvesting of the hedgerows in ACS should be performed in a way that a constant wind protection is ensured. Accordingly, hedgerows should not be harvested completely at the same time. If the hedgerows consist of four or more tree rows, it is more useful to cut only a half of the tree rows at one harvest and harvest the remaining half in the following seasons (Quinkenstein et al. 2009a).

The economic value of mixed land-use systems can be assessed by using the land equivalent ratio (LER). Using this ratio, the yields from growing two or more crops in a mixed stand and the yield obtained from growing the same crops in monoculture can be compared. LER is defined as the land amount equivalent needed by one type of crop to break even in physical terms (i.e. Mg ha^{-1}) with what is yielded of 1 ha by another (Mead and Willey 1980; Grünewald et al. 2007). The LER is calculated according to Eq. (10.1):

$$\mathrm{LER} = \sum_{i=1}^{n} \frac{\mathrm{mixed}_{\mathrm{crop_i}}}{\mathrm{mono}_{\mathrm{crop_i}}} \tag{10.1}$$

where *mixed* denotes the yield of *crop i* in the mixed stand and *mono* denotes the yield of *crop i* in the monocultural stand. An LER greater than 1.0 usually shows that mixed cropping is advantageous, while less than 1.0 shows that it is disadvantageous. For an experimental ACS with black locust and alfalfa (*Medicago sativa*) established at an experimental plot on post-mining sites in the Lusatian region, an LER of 0.98 was reported by Grünewald et al. (2007), showing that under the local growth conditions, the productivity of alfalfa for an ACS and for monocultural cropping does not differ substantially (Grünewald et al. 2007). Other authors predicted an LER between 1.0 and 1.4 for silvo-arable systems within the European climatic region, suggesting that intercropping would be a more efficient land-use option than monocultural cropping (Graves et al. 2007).

To which actual extent the productivity of agricultural mixed systems differs from that of monocultural systems depends on the site management and abiotic site conditions but also on the specific characteristics of agricultural interactions at the considered site. In this context, microclimatic factors play a decisive role, as they influence important growth factors such as water availability to the crops.

6 Assessing Ecosystem Services Focusing on the Effects of Land Use on Productivity and Soil Fertility

The previously described complexity of ACS makes a comprehensive assessment of the inherent processes challenging. Establishing extensively managed strips of fast-growing trees on agricultural land leads to extension of the overall management and thus related enhanced provision of ES, which are also known as benefits provided to human population by the ecosystems (Costanza et al. 1997; Daily 1997; Reid et al. 2005). The concept of ES can be understood as an approach aiming to improve the understanding regarding benefits provided by nature, by describing the dependence of human well-being on these benefits and valuing them in economic terms (Marzelli et al. 2014). In this context, assessing ES is necessary to fully account for the environmental, economic and social effects of cultivation strategies and ultimately adequately reward the providers of ES. According to the Common International Classification of Ecosystem Services (CICES), they have been broadly classified into (i) provisioning (all nutritional, material and energetic outputs from living systems); (ii) regulation and maintenance (include mediation of waste, toxics and other nuisances, mediation of flows and maintenance of physical, chemical and biological conditions); and (iii) cultural (obtained from physical, spiritual and other interactions with biota, ecosystem and landscape) (Haines-Young and Potschin 2013).

The type, magnitude and relative mix of services provided by the ecosystems is influenced by management decisions which cause trade-offs between them, i.e. reduced provision of one ES because of increased provision of another service (Rodríguez et al. 2006). For example, agricultural ecosystems are primarily managed to optimize provisioning ES, but in the production process, they depend on many regulating ES, such as pollination, biological pest control, soil fertility, nutrient cycling and hydrological services (Zhang et al. 2007; Power 2010). Consequently, agricultural management which focuses on provisioning ES induces a trade-off with regulating and cultural services (Raudsepp-Hearne et al. 2010; Maes et al. 2012a). On the other hand, agriculture offers an opportunity of enhanced ES provision, among others, by application of land management regimes that favour the provision of ES (Porter et al. 2009). Hence, appropriate management strategies can ameliorate many of the negative impacts of agriculture, while at the same time largely maintaining provisioning services (Power 2010). According to the literature and recent research results, diverse farming systems, like agroforestry, were found better at providing ES than conventional agriculture (Jose 2009; Quinkenstein et al. 2009a; Kremen and Miles 2012; Smith et al. 2012; Tsonkova et al. 2012). In the attempt to optimize the effects of land-use strategies, such as agroforestry, a suitable approach is to assess the ES provided by this system.

The available tools for assessing ES provided by different land-use systems range from simple spreadsheet models to complex software packages (Bagstad et al. 2013). Information based on mapping and modelling exercises has been used to analyse the spatial distribution of multiple ES at various scales (Maes et al. 2012b). Typically, planning studies are carried out on subnational levels, while studies focusing on general trends like spatial distribution of ES are carried out on continental or global level (Maes et al. 2012b). For a regional or local assessment data, sources with higher spatial resolution should be used (Marzelli et al. 2014). Moreover, the influence of site conditions and management decisions should be more precisely reflected in the ES assessments. For example, multifunctional landscape models used to map and value ES often do not adequately include the impacts of land use and management on soil properties, due to model limitations and lack of ability to account for complexity and feedbacks in the systems (Dominati et al. 2016). Considerable differences in the provision of ES, as well as economic value under the same land use (permanent pasture grazed by dairy cows) for two contrasting soil types in New Zealand, were modelled by Dominati et al. (2016).

Moreover, provision of simple methods or data support tools to farmers can improve the adoption of appropriate land management approaches at the farm scale (Buckwell et al. 2014). Local decisions regarding benefits of ACS in comparison with conventional agriculture on a farm scale could be supported by simple tools, such as the ecosystem services assessment tool for agroforestry (ESAT-A), which linked indicators with ES, while taking into account the spatial heterogeneity of the field (Tsonkova et al. 2014). Essential for such an approach is using simple and well-acknowledged methods which provide reliable results without lacking scientific rigour. Data required as input in ESAT-A rely temporally on average yearly values and spatially on the farm field that would be designated to ACS and were related to descriptions of soil, climate as well as the field management (Tsonkova et al. 2014). The indicator results were linked to relevant regulating ES which enabled the assessment of several ES, supplied by ACS in comparison with conventional agriculture, conducted for hypothetical scenarios representing various site conditions of agricultural fields in Germany (Tsonkova et al. 2014). Moreover, the results could be also used as input to already establish software as it was demonstrated by Tsonkova et al. (2015), who identified target scenarios for establishing ACS by using the method of partial order ranking. The authors suggested that partial order ranking was a useful tool to objectively identify fields, where provision of ES could be enhanced by planting ACS, as it ranked the scenarios, while retaining their spatial configuration and information provided by the indicator set (Tsonkova et al. 2015). This study however did not include assessment of provisioning and cultural ES.

In the context of assessing ES provided by European agroforestry systems, a recent review suggested the focus was set on traditional agroforestry systems like wood pastures in the Mediterranean and hedgerow systems in the Atlantic and Continental regions (Fagerholm et al. 2016). Most of the studies assessed regulating as well as provisioning services, such as provision of habitat and biodiversity, food, climate regulation, fibre and fuel, while the consideration of cultural services has been largely limited to aesthetic value (Fagerholm et al. 2016). Torralba et al. (2016) conducted a meta-analysis on the effects of agroforestry on ES provision and biodiversity in Europe and concluded that compared to conventional agriculture, agroforestry can enhance the provision of ES and biodiversity. Erosion control, biodiversity and soil fertility were generally enhanced by the agroforestry systems considered, while the effect on provisioning services was not clear (Torralba et al. 2016). It was suggested that a negative effect on biomass production for silvopastoral agroforestry was possible (Torralba et al. 2016). The authors, however, did not consider ACS for production of biomass which is discussed in this study.

6.1 Productivity in ACS

The extensification of production via ACS did not lead to a reduction of the yield on a hectare basis, but rather the opposite was shown by several studies calculating LER, a useful indicator for assessing the productivity of agroforestry in comparison with agricultural practices (see above). Further studies assessing this indicator are necessary to optimize production from agroforestry under different conditions, considering the distance between hedgerows and value of LER obtained (Tsonkova et al. 2012). In general, the productivity in temperate agroforestry could be predicted by tools like Yield-SAFE, a model which can describe the yields of crops and trees in agricultural, agroforestry and forestry systems (van der Werf et al. 2007). Yield-SAFE has been recently enhanced in order to predict more accurately the provision of ES by agroforestry systems relative to forestry and arable systems (Palma et al. 2016). However, yield models usually require sets of input variables linked to inter alia soil, crop and climate characteristics which are not always known (Vooren et al. 2016) or cannot be easily obtained.

Therefore, a feasible approach of assessing yield of fast-growing trees, under consideration of different pedogenic and climatic conditions, is to use statistical data, average yields or regression models (Ali 2009; Röhle et al. 2010). Furthermore, the effect of tree rows on crop yield could be assessed relatively to the height of trees and the distance of the crop to the adjacent row as demonstrated by Vooren et al. (2016). The calculations of the authors considering the effect of tree height, based on results collected from temperate ACS, showed that compared to a treeless situation, relative crop yield was 70% starting from the tree row, over a distance of 1.64 times the tree height, and 107% between 1.64 and 9.52 times the tree height (Vooren et al. 2016).

A crucial factor in yield estimation in agroforestry systems is taking into account for the interactions between crop and tree components. The advantages of tree hedgerows to improving the yield of adjacent crops, because of microclimate modifications, have been broadly investigated in the literature (see above). In this context, the design of ACS regarding the height, orientation and width of tree rows is crucial to maximize the potential benefits and optimize the productivity of the system. The magnitude of benefits to the crop is in addition dependent on the type of crop planted, as their response to microclimate modifications varies (Kort 1988). The effect on the microclimate would be nevertheless captured in the yield and could be assessed through the overall system productivity. Furthermore, productivity is closely linked with soil fertility which can be measured by the effect of trees on soil nutrients and C.

6.2 Soil Fertility

6.2.1 Soil Nutrients

Agroforestry could contribute to soil fertility by promoting a more closed nutrient cycling than agricultural systems (Young 1990). The difference between the amount of all nutrient inputs entering the system and the quantity of nutrient outputs leaving the system produces the nutrient balance, an indicator of soil fertility (Roy et al. 2003; OECD 2008). A nutrient deficit suggests declining soil fertility, while a nutrient surplus suggests a risk of air and water pollution (OECD 2008). In intensively managed systems, nutrients which are exported from the system with harvest have to be yearly compensated for by using fertilizer inputs. For example, the export of nutrients for agricultural crops like silage maize is high, if the total aboveground biomass is utilized for energy production (Böhm et al. 2012). Increased fertilizer use in agriculture incurs financial costs, and excess application induces further loss of nutrients and thus related pollution of the environment (Baligar et al. 2001; Cassman et al. 2002).

On the other hand, perennial crops combine high biomass productivity with low requirements for fertilizer inputs (Böhmel 2007). The harvest of fast-growing trees usually takes place in the winter months, and the leaves, containing a high proportion of the absorbed nutrients by the tree, remain on the field (Böhm et al. 2012). They add to the soil nutrient pool, and the available nutrients can be once again taken up by the plants during growth. Thus, no external addition of nutrients is required, as the amount of nutrients exported is low. The lower nutrient export following harvest of fast-growing trees was also related with their higher nutrient use efficiency (Quinkenstein et al. 2009a). Nutrient use efficiency (NUE) emphasizing the internal nutrient requirement of the plant was defined as the total amount of harvestable biomass produced per unit of nutrient absorbed (Adegbidi et al. 2001) and was identified as a useful indicator for assessing soil fertility (Tsonkova et al.

2014). Maximizing biomass production using species with high NUE, hence lower nutrient removal at harvest, is desirable from the perspectives of both economics and environmental sustainability (Adegbidi et al. 2001). In the context of ACS, the overall NUE of the system is improved, as the NUE of the tree strips is higher; hence the nutrient export with harvest is lower than in conventional agriculture (Quinkenstein et al. 2009a). Thereby, the nutrient pool under the tree strips of the ACS is sustained in the long term.

Calculated nitrogen (N) balances for willow and poplar trees in the temperate region were shown to be positive, suggesting a build-up of organic N, while at the same time, low amounts of N were lost to the atmosphere and groundwater (Updegraff et al. 1990; Lamersdorf and Schulte-Bisping 2010; Pugesgaard et al. 2015). The former loss refers, for example, to emissions of nitrous oxide (N_2O) which were generally estimated to be lower from perennial cultures as compared to annual crops (Hellebrand et al. 2010). The latter was related to leaching of nitrate (NO_3) which was reduced in agroforestry as reported by several authors summarized among others by Tsonkova et al. (2012). For the assessment of nitrate leaching besides N balance, also determining seepage rate is necessary (Feldwisch et al. 1998). The method of Wessolek et al. (2004) which differentiates between forms of land use, groundwater influence and the plant-available water threshold is a useful approach in this regard. Moreover, assessing seepage rate is important as planting fast-growing trees has been associated with a reduction in water availability, especially where precipitation was low or even when dry summers occurred in areas with otherwise adequate precipitation (Dimitriou et al. 2009). This implied that in such cases for ACS, a trade-off could be expected between water regulation and water quality (Tsonkova et al. 2014).

Moreover, surface water quality can be seen as an additional improvement due to ACS as the export of nutrients with erosion and surface runoff was reduced (Tsonkova et al. 2012, 2014). In this context, the assessment of phosphorus loss is important which is largely determined by the phosphorus concentration in soil and the amount of soil lost with erosion (Feldwisch et al. 1998). In ACS the erosion by wind and water is minimized as trees act as a barrier and provide plant residues which also influence the amount of C_{org} in soil (see above).

6.3 Soil Carbon

The interaction between SOC and agricultural land management can be estimated by simple tools such as humus-balancing methods (Brock et al. 2013). These methods refer both to simple models aiming to quantify SOM change in arable soils, or SOC change in particular, and models that refer to the optimization of soil productivity in arable soils by calculating demand of organic fertilizer, without quantifying the change in SOC (Brock et al. 2013). A method belonging to the latter group developed by the Association of German Agricultural Analytic and Research

Institutes 'VDLUFA' Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungs Anstalten (Körschens et al. 2004) has proven especially suitable in the agricultural practice due to its user friendliness (Kolbe 2010). In this method, the organic matter supply and depletion effects were considered by using C_{org} decomposition coefficients which describe the maximum decreasing or increasing effects of a specific long-term cultivation method or supply of organic matter on the SOC stocks (Kolbe 2010). The cultivation of crops increasing SOC, e.g. grasses and legumes, as well as addition of various types of organic manure is assumed as an increase, and positive coefficients are used (Körschens et al. 2004; Kolbe 2010). The loss of SOC results from the cultivation of humus-depleting crop species, e.g. root and tuber crops, resulting from the provided low crop residues and is depicted by specific negative coefficients (Körschens et al. 2004; Kolbe 2010). In conventional agricultural management, a reduction of SOC is an indicator of reduced soil fertility and thus related productivity, while an increase of SOC may be related with increased mineralization, loss of N and reduced NUE (Körschens et al. 2004). Hence, the method aims at optimizing crop management by preserving the typical SOC content at the field.

Perennials on the other hand demonstrate strong positive effects on the humus balance due to provided litter and root residues and the lack of tillage (Hüttl and Dominik 2008). The positive effect of trees on SOC was described in detail in the previous section. Average values for the effect of fast-growing trees over a long-term period could be calculated from long-term experiments. The average annual increase in SOC stocks over 20 years of management calculated by Tsonkova et al. (2014) was of similar magnitude to the average annual increase in SOC stocks under forest soils, measured in Germany between the first and second National Forest Inventories in 1990 and 2006, respectively (Bolte et al. 2011). The increase in SOC under trees was especially important for soils of low quality, or soils with low initial SOC content (Coleman et al. 2004). Although typical concentrations of SOC vary for different soils, it was argued that a major threshold below which potentially serious decline in soil quality would occur was 2% SOC (Loveland and Webb 2003). Accordingly, in the assessment of Tsonkova et al. (2014), soils of low quality were particularly shown to benefit if an ACS was planted, as the highest increase in soil C was predicted for scenarios with lowest initial SOC content below 1%. Moreover, even for scenarios with sandy soil texture, generally most susceptible to leaching, the nitrate concentration in groundwater was significantly reduced in ACS as compared with conventional agriculture (Tsonkova et al. 2014). Furthermore, on low-quality soils, the cultivation of fast-growing trees did not compete with crop production and could result in the provision of additional benefits (Schulze et al. 2016). Hence, the provision of both market and non-market ES is enhanced under ACS; however, only for provisioning ES, there is an established market price, while for regulating and cultural ES, no market currently exists.

6.4 Market and Non-market ES

Valuation of ES from agroforestry systems suggested that the value of market ES was surpassed by the value of non-market ES. For example, the value of market and non-market ES provided by a mixed system with fast-growing trees (hazel, *Corylus* spp.; willow, *Salix* spp.; and alder, *Alnus* spp.) combining food and energy production in Taastrup, Denmark, was calculated by Porter et al. (2009). After taking into account the proportional areas of the pasture (45%), cereals (45%) and biomass (10%), the value of the non-market ES considered for the system comprised 64% of the total economic value (Porter et al. 2009). The largest contributions of non-market ES came from regulation of N turnover and a contribution to landscape aesthetics (Porter et al. 2009). Similarly, the monetary values of non-market ES provided by a tree-based intercropping system in Canada amounted to 65% of the total value of the ES considered (Alam et al. 2014). Of the ES which had no market price, water-quality regulation ranked highest, followed by air quality regulation and C sequestration. The study showed that although conventional agriculture provided more private benefits than agroforestry, the value of ES provided to society in agroforestry was much higher compared to this private value (Alam et al. 2014). A comparison regarding the provision of market and non-market ES by conventional agriculture and ACS is hypothetically illustrated in Fig. 10.5.

The provision of ES from ACS is much higher than ES from conventional agriculture, but only approximately one-third of this value is reflected in the market. Due to the increase in SOC by plant residues, soil fertility is maintained, and the losses of nutrients from the soil are minimized which results in a favourable N balance with no losses to the atmosphere and groundwater. Therefore, ACS enhance the provision of market services, i.e. crop and tree production, as well as the provision of non-market benefits, which is greatly influenced by the improvement in SOC and nutrient balance. In ACS, the provision of crop yield could be somewhat reduced as a small proportion of the land would be dedicated to planting trees. Nonetheless, in addition to obtaining tree yield, the provision of regulating and cultural services is enhanced; as in addition to maintaining soil fertility, trees provide shelter from the wind and improve water quality, biodiversity and system aesthetics (Tsonkova et al. 2012). However, planting trees requires somewhat higher initial investment, and the revenues are not yearly obtained as in the case of cultivating conventional crops. Therefore, efficient programs to support farmers are crucial for the establishment of agroforestry, thereby optimizing the effects of agricultural production. In this context, improving the financial support for agroforestry, e.g. by providing payments for provision of non-market benefits, is essential to promote this sustainable land-use system and enhance its relevance in the practice.

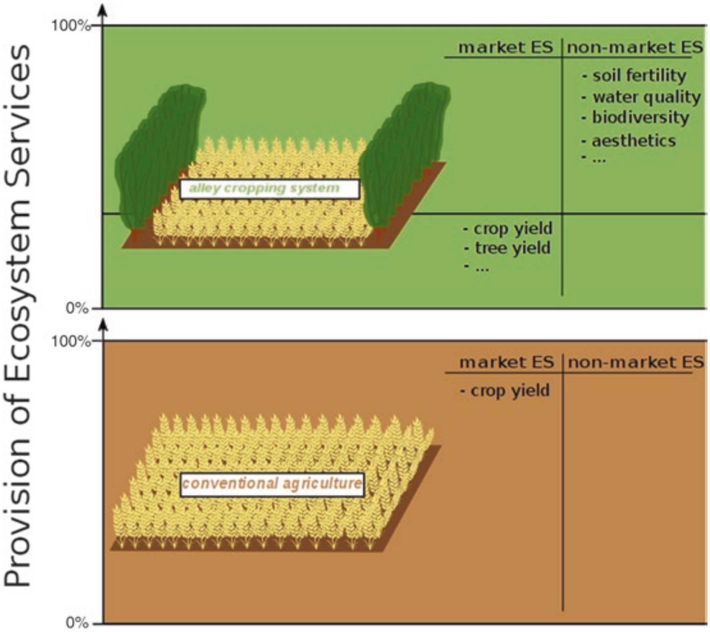


Fig. 10.5 Compared provision of market and non-market ecosystem services by conventional agriculture (colour, brown) and alley cropping (colour, green). The value of market ES represents approximately one-third of the total ES provided by alley cropping (Porter et al. 2009; Alam et al. 2014). The crop yield in alley cropping may be lower, due to the area planted with trees, but in addition trees provide yield and shelter from the wind, maintain soil fertility and filter nutrients which otherwise would cause water pollution and improve biodiversity and system aesthetics

7 Conclusions

The discussed findings demonstrate that through site-adapted ACS systems, in many cases, negative effects of microclimatic stress factors for crop production, such as excessive wind or temperature extremes, can be mitigated. In addition, the discussed effects of ACS on SOM underline the important role that agricultural trees can play regarding the build-up and maintenance of substantial stocks of SOC in agricultural soils which is essential for sustaining and enhancing productivity of agricultural land in the long term. In this regard, a promising management strategy for the sustainable preservation of SOC seems to be the establishment of a rotation system, within which the cultivation of trees and conventional crops alternates on the same piece of land. Such a rotation would make soil areas, improved by trees regarding SOC, soil structure or soil life, available for agricultural crops, while conventionally used areas would be planted with trees in the subsequent rotation. In addition, the assessment of ES in ACS, focusing on site productivity and soil fertility, revealed that the provision of ES for which currently no market exists, typically, is higher than the provision of market goods. Hence, providing payments to farmers reflecting the total value of provided benefits is expected to enhance the practical relevance and application of ACS as a tool to optimize the effects of agricultural production.

Summarizing, the discussed characteristics of ACS suggest that the combination of agricultural trees and annual crops in ACS can function as a practical tool for improving the growing conditions for crops on agricultural sites regarding microclimatic conditions, SOC stocks and provided ES. However, the exact expression and characteristics of the discussed effects depend on the specific site, management, weather and other local growing conditions. In this regard, the overall advantage of ACS (and other agroforestry systems) is its flexibility, so that many relevant stress factors for agricultural production can be influenced and (to some degree) be modified in a way to mitigate negative effects and to sustain crop production. Furthermore, many potential disadvantages for crop production in ACS, which may arise due to competition effects between trees and crops (e.g. water stress in the rooting zone or shading by the trees), can be managed by appropriate measures (e.g. species selection, modifying planting density, root pruning by ploughing or regular cutting of the tree canopies). As complex multifunctional land-use systems, ACS are suitable to handle different usage scenarios and different objectives. If, for example, wind protection is the major issue, the crop alley widths in ACS can be optimized to maximize the wind protection effect. If woody biomass production needs to be increased, the area share of trees can be increased, the planting density and rotation length can be adjusted or, for example, if the protection of waterbodies is the main issue, the hedgerows can be aligned along riversides.

However, the interplay between management, plants, microclimate and soil in ACS is very complex and requires a careful planning of the system and land management. For this reason, more research is needed to better understand the interplay of identified interactions in ACS. An increased knowledge in this field could function as a basis to develop a more comprehensive support strategy for farmers who choose to establish ACS on their land. First steps could include the development of a subsidy system for the provision of non-market ES by ACS and the preparation of application-oriented guidelines of how to adapt ACS to different practical usage scenarios.

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Chapter 11
Soil Organic Carbon Stocks Under Different Agroforestry Systems of North-Eastern Regions of India

K. M. Manjaiah, S. Sandeep, T. Ramesh, and M. R. Mayadevi

Abstract Increasing concentrations of greenhouse gases, especially carbon dioxide, and exploring ways and means to mitigate them is a major challenge to the global community. Exploring terrestrial sinks of carbon is suggested as one of the options, and in this context agroforestry systems, with a mix of trees and crop plants, offer a good solution. India's North-Eastern Hill region has a rich tradition of agroforestry systems and is estimated to store between 85.34 and 121.87 Mg C ha^{-1}. However, stability of the stored soil carbon is a function of both quality of inputs and their interaction with soil components. Thus, agroforestry systems in the North-Eastern region spanning a wide range of climatic conditions ranging from alpine to tropical, rainfall pattern, vegetation, topography, land use, ethnicity, and cultural diversity vary in their carbon accumulation and sequestration potentials. Here, in this chapter we have attempted to review and synthesize the current knowledge on soil organic carbon sequestration status and processes in the agroforestry systems of North-Eastern Hill region.

Keywords Agroforestry · Carbon sequestration · North-Eastern region · Soil organic carbon

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1 Introduction

Sustaining and improving soil organic carbon (SOC) levels is essential for ensuring ecosystem health and productivity (Katyal et al. 2001). In addition to being a primary source of plant nutrients, SOC also stores a good amount of carbon and thereby helps in maintaining the overall environmental quality (Houghton 2007). Increase in greenhouse gas (GHG) concentration in atmosphere is considered as a major cause of global warming. The Intergovernmental Panel on Climate Change (IPCC 2007) estimates that the current GHG, especially CO_2, concentrations in the atmosphere have increased drastically and are about 30% more than the preindustrial levels. Global anthropogenic emissions of carbon dioxide to the atmosphere are mainly contributed by fossil fuel combustion and conversion of tropical forests to agricultural production lands (Lorenz and Lal 2015). Lal et al. (1998) reported that terrestrial carbon storage offers a good option to offset the annual atmospheric CO_2-C increments and suggest a 0.01% soil carbon content increase globally to achieve this goal.

Plant and soil carbon is estimated to represent nearly 25% of global carbon stocks (2000 ± 500 Pg). These carbon sink options can be significantly enhanced by judiciously managing or manipulating various biomes. In this connection, agroecosystems have the potential to remove and store about 42–90 Pg carbon from the atmosphere in a span of 50–100 years. Further, the dynamic relationship between plants and SOC depicts that changes in vegetative cover could have an influence on the global carbon budget by increasing or decreasing the terrestrial carbon storage.

Agroforestry is considered worldwide as a good option to address the problems arising from forest land conversions and subsequent positive carbon feedbacks to atmosphere. These systems strive to retain, introduce, or judiciously mix woody perennials or trees with crops, pastures, and livestock and derive ecological and economical benefits from their interactions (Nair 1993; Young 1997). Historically agroforestry systems have been practiced for sustainability and maintaining soil health. In recent times, it has been accepted as a sustainable alternative to single crop systems and shifting cultivation (Dixon 1995; Young 1997). Based on their end uses, tree components in the agroforestry systems provide for long-term carbon sinks. Sequestration of carbon in the agroforestry systems occurs in the aboveground and belowground biomass portions as well as soil. Their capacity to produce large volumes of biomass and extensive roots demands that this agroecosystem receives a wider attention in climate change mitigation strategies. Nair et al. (2010) estimated that the agroforestry systems have a capacity to store approximately 30–300 Mg C ha^{-1} in a 1 m soil depth.

Several agroforestry forms and methods are common throughout India. In North-Eastern region, this has evolved through generations and has seen a gradual cropping intensification. Shifting cultivation or *jhum* is the major agroforestry system practiced in the region wherein farmers maintain a high species diversity and the entire socioeconomic fabric depends upon this system. However, with shortening of rotation period, shifting cultivation has become ecologically less sound and resulted in land degradation. Other agroforestry systems practiced in the region are agri-silviculture, agri-horticulture, silvi-horticulture, pastoral silviculture, silvopastoral systems, and homegardens, each of which has immense potential to store carbon. North-Eastern region with its large diversity in climatic conditions and physiography supports these agroforestry systems in a wide range of soils and sequesters a high level of organic carbon in them compared to agricultural lands.

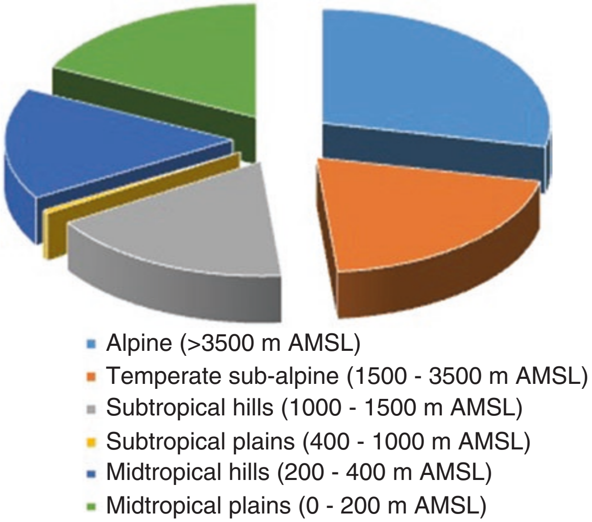
2 Major Agroforestry Systems in North-Eastern Hill Region

Agroforestry, defined as the practice of growing trees alongside farming, is a major practice in North-Eastern Hill (NEH) region and plays an important role in livelihood and land productivity enhancements. Such practices offer a multitude of functions ranging from soil and water conservation, soil fertility improvement, prevention of water logging, and eutrophication and biodiversity enhancement. Besides providing livestock fodder, they help reduce the pressure on natural forests for fuel and above all offer good carbon sequestration opportunities. They also enhance the system resilience to cope up with adverse climate change.

North-Eastern region has a rich tradition of agroforestry practices. The agroforestry systems in this region include trees grown on agricultural lands, community forestry, and a variety of ethno-forestry practices. NEH region comprising of seven Indian states (Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura) spans an area of approximately 1,83,750 km^2 (Anonymous 2005). The region occupies a distinct position in the Indian subcontinent by way of its geographical position, altitudinal variations from 15 to 5000 m above mean sea level, typical physiography, precipitation, and alternating pressure cells in the Bay of Bengal and North-West India. The presence of tropical mountain air masses along with local winds develops a range of climate from tropical to alpine type and influences the regions' vegetation type (Barthakur 2004). This diverse yet unique climate has led to a rich biodiversity hotspot in this part of India with a varying forest type distribution from tropical moist evergreen to alpine forests. Rural population accounts for 80% of total population, and a clear majority derive their livelihood from agriculture and its allied sectors. Based on the climate, topography, soil, and type of dominant crop and livestock species, the North-Eastern region has been divided into six distinct agroclimatic zones as given in Fig. 11.1.

In the North-Eastern region, there exists a long tradition of deliberately planting trees alongside farm crops, and as such various agroforestry models exist that integrate crop husbandry, aquaculture, livestock, etc. to replace the *jhum* cultivation and complement soil productivity and promote sustainable production (Bhatt et al. 2006; Kirby and Potvin 2007; Nair et al. 2009a; Ramesh et al. 2013). Some of the major agroforestry systems in the region include homegardens, multistoreyed agroforestry systems, agri-horti-silviculture, horti-pastoral systems, agri-silviculture, and agri-horti-silvopastoral systems. Trees such as *Alnus nepalensis*, *Areca catechu*,

Fig. 11.1 Area distribution of different agroclimatic zones in North East India



Pinus kesiya, *Schima wallichii*, *Prunus domestica*, *Pyrus communis*, etc. are usually planted along with crops like coffee, ginger, maize, pineapple, and vegetables.

The climatic conditions and economic advantages are considered the major driving forces in selection of an intercrop and tree species in the region. Besides meeting the multifaceted farmer's needs such as economic produce, feed, timber, fuelwood, etc., agroforestry systems also provide several environmental benefits, viz., carbon storage in soil and tree biomass, thus reducing the positive feedbacks of carbon to atmosphere.

3 Carbon Stocks and Dynamics Under Different Agroforestry Systems

Carbon sequestration entails the transfer of carbon from atmosphere, especially CO_2-C and its safe storage in recalcitrant pools with long turnover times (UNFCCC 2007). The earth surface systems comprising of atmosphere, oceans, biosphere, and soil control the long-term biogeochemical cycling of global carbon over geological time scales of more than 100,000 years (Berner 2003). Ecosystem systems such as forest, agroforestry, and agricultural systems worldwide are considered potential sinks for atmospheric carbon. In this context, agroforestry systems will have a great impact on long-term carbon storage and fluxes in the terrestrial biosphere under the assumption that area under this system will substantially increase in the near future (Dixon 1995).

The agroforestry systems' potential for long-term carbon storage depends on the biological CO_2 uptake and its subsequent conversion to long-lived, inert materials, i.e., bio-sequestration (U.S. DOE 2008). Bio-sequestration can temporarily immobilize carbon from active cycling and, in particular, convert CO_2 from one reservoir into another with longer turnover times (IPCC 2007). Carbon movement from the atmospheric reservoir to biotic or terrestrial pools could be considered accumulation as this process genuinely contributes to the climate change mitigation (Powlson et al. 2011). It should also be noted that increasing carbon stocks in agroforestry systems within a given period of time is a single step, whereas the sequestration potential of the system also depends on the fate of those stored carbon. Carbon sequestration occurs in soils of agroforestry systems both directly and indirectly. Direct sequestration occurs by conversion of CO_2 to inorganic compounds (e.g., calcium and magnesium carbonates), whereas indirectly it occurs by plant CO_2 fixation into biomass which gets subsequently added as SOC during decomposition processes. Soil carbon sequestration concepts and mechanisms, though similar across these systems, manifest differently depending on their specific characteristics. The magnitude of variation (increase/decrease) in soil organic stocks depends on the type and degree of land use, its changes, and land management.

NEH region with a high variability in climatic conditions ranging from alpine to tropical, rainfall pattern, vegetation, topography, land use, ethnicity, and cultural diversity is also found to be highly variable in the organic carbon contents of soil. In general, soils of this region are low in nutrient reserves, exchangeable bases, and organic matter content and mild to strongly acidic with high aluminum toxicity. As such, the agroforestry systems' potential to increase carbon stocks on the infertile acid soils of NEH region appears to be variable. The SOC stocks of the major land uses (excluding the area under settlements, water bodies, and snow-covered areas of Sikkim) are given in Fig. 11.2.

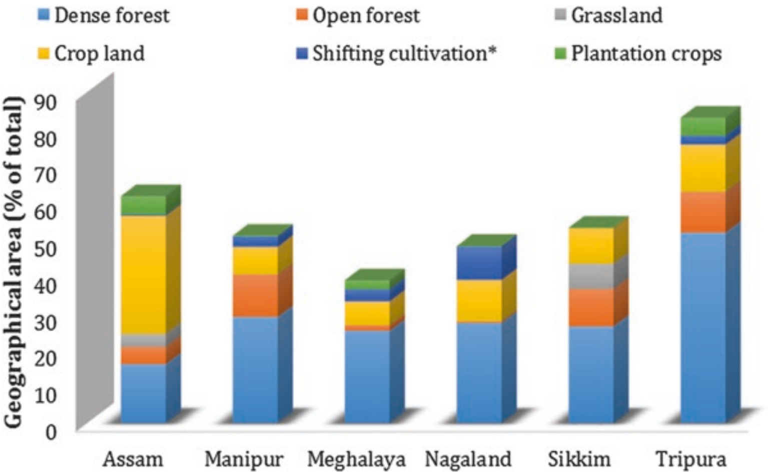


Fig. 11.2 Land use – land cover distribution of North-Eastern region (2004–2005) (*Current + abandoned: Source NRSA 2011)

Carbon storage in an agroforestry system should be considered a dynamic process that can be split into different phases. These systems during their establishment phases are most likely to be carbon sources due to rapid carbon and nitrogen losses from soil as well as vegetation. This will be followed by a phase of quick accumulation, and during maturation of the tree species, large quantities of carbon will be accumulated in the tree parts and soil. A good amount of carbon is returned to the atmosphere when the trees are felled and new cropping is taken up on the land (Dixon 1995). Hence agroforestry systems that produce a positive net accumulation from the initial carbon stock position after a few rotations alone can be considered to sequester carbon in the long run.

Conversion of natural forests to croplands or even agroforestry systems reduces its carbon stocks. SOC contents in the surface layers of managed plantation and *jhum* fallows were observed to be less than natural forest to the tune of 51.68% and 48.55% in Tripura. Studies have also shown that in all land uses of the region, SOC stock decreases toward the lower layers. In general, from 0–10 to 10–30 cm soil depth, there is a reduction in 8.4–43.3% organic carbon content among natural forest, managed plantations, and *jhum* fallows. Reduction in soil fertility and crop productivity, residue removal, burning, soil erosion, bare fallowing, and intensive tillage are attributed as some of the causes for large losses of SOC on cultivation of virgin soil (Lal and Kimble 2000; Paustian et al. 2000). The total organic carbon stock (up to 1 m depth) of these systems was found to vary from 85.34 to 121.87 Mg C ha^{-1}. Modifying silvicultural systems is suggested to rapidly maximize carbon accumulation in these systems. Total soil organic stocks under major land use systems of NEH region are shown in Fig. 11.3.

The most dominant and traditional cultivation practice in NEH region is shifting cultivation (*jhum* cultivation) where approximately 3869 km^2 area is brought under this system every year and has been reported to have the lowest carbon stocks among the different land uses. Shifting cultivation in the region involves clearing

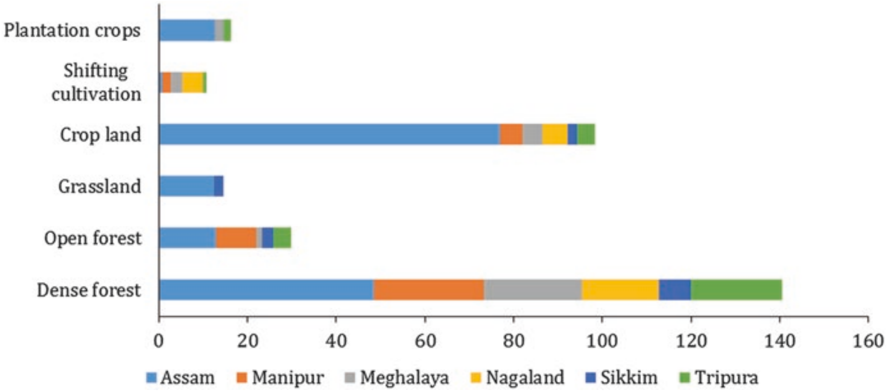


Fig. 11.3 SOC stock (Tg) under major land use systems of North-Eastern region (Source: Choudhury et al. 2011)

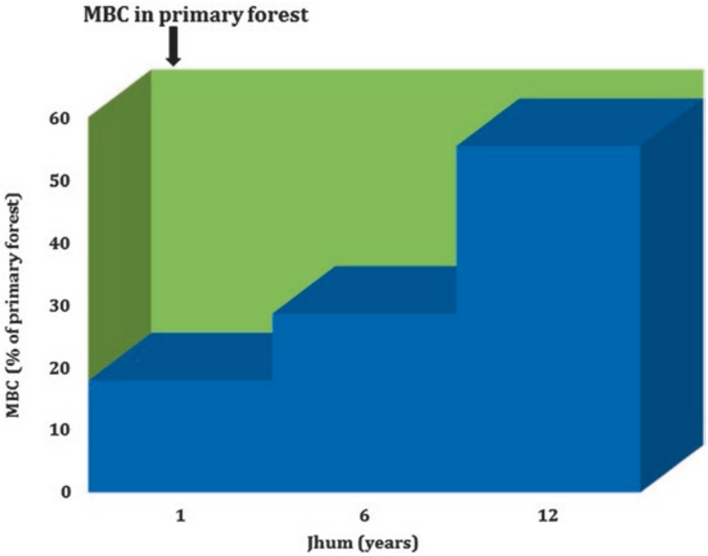


Fig. 11.4 Variations in microbial biomass carbon (MBC) content with jhumming age in North East India (Source: Ralte et al. 2005)

forest lands in steep slopes and burning followed by seed sowing with onset of rains. The continuum of processes physically exposes the soil for planting, eliminates vegetation cover, and usually has a short rotation period of 2–3 years. This leads to rapid soil degradation and hence carbon storage. For example, microbial biomass carbon (MBC), a major soil carbon pool and an indicator of soil health, was observed to decline rapidly by clearing and burning of forests for shifting cultivation in the region (Fig. 11.4). However, with passage of time, this carbon fraction was found to recuperate by way of steady buildup of organic matter and nutrients with successional stage of the ecosystem. The detritus and nutrients provided by these ecosystems act as the basic source for MBC buildup in *jhum* areas with age.

Agroforestry plays a decisive role in microclimate of soil, availability of substrates and carbon allocation patterns in plant, and thereby the CO_2 efflux from soil to atmosphere. These systems continuously return large amounts of organic material from the standing biomass and help build stable carbon pools in soil. The quantity of carbon and nutrient inputs to the soil in agroforestry systems is directly dependent on tree and crop composition productivity, management system, and site-specific edaphic and climatic factors (Nair 1993). The quality of the added organic inputs is yet another key factor controlling the decomposition rate and nutrient release (Kwabiah et al. 1999, 2001). Multipurpose tree species used in agroforestry systems of the NEH region were found to improve both the quantity and quality of SOC as a function of soil type and climate in the region (Parton et al. 1987; Saha et al. 2007). Several studies (Saha and Jha 2012; Ramesh et al. 2013) in the NEH region have reported an improvement of approximately 20–32% carbon when mul-

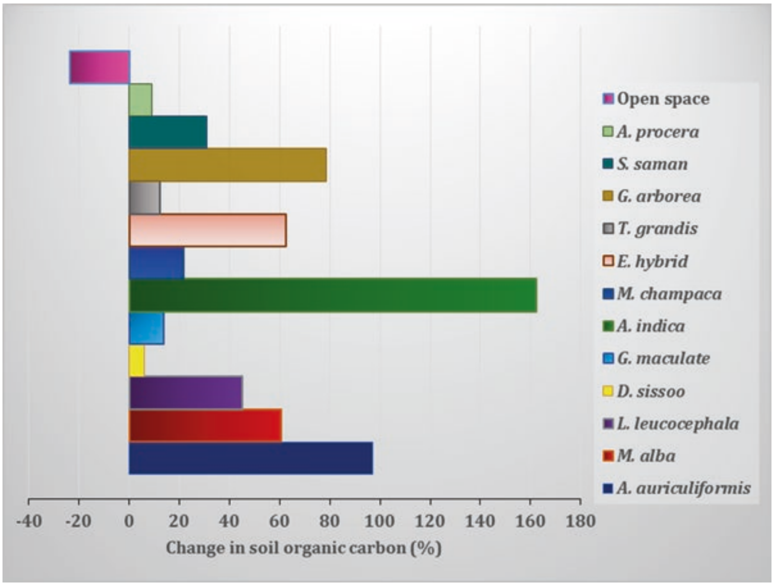


Fig. 11.5 Changes in SOC (%) over the years (between 4th and 16th year) under various multipurpose trees in North East India (Source: Datta and Singh 2007)

tipurpose tree species were grown alongside crops. The quality of the stored carbon was also found enhanced with respect to cellulose, hemicellulose, carbon/nitrogen and lignin/nitrogen ratios.

Roots contribute approximately 20–25% of the total tree biomass, and the constant addition to soil organic matter pool through leaf and root decay furthers the carbon status improvements in the agroforestry systems (Balkrishnan and Toky 1993). The enhanced soil carbon accumulation can also be attributed to the better soil aggregation and higher vegetative cover throughout the year in these systems. Several other studies (Saha et al. 2007, 2010) have also reported an enhancement of SOC up to 160% under various multipurpose tree species used in the agroforestry systems of the region. The carbon enrichment under agroforestry system occurs with greater vegetative cover, enhanced litter, and extensive root distributions (Figs. 11.5 and 11.6). Similarly, tree species such as *Pinus kesiya* when used in agroforestry systems lead to carbon accumulation by way of generating acidic pine needles that lower soil pH, thereby reducing the rate of SOC decomposition. In general, multipurpose tree species used in the region in agroforestry systems improves the SOC content of soil though to varying degree depending upon the type of system, their structure and function, nature and composition of trees and crops, and management options.

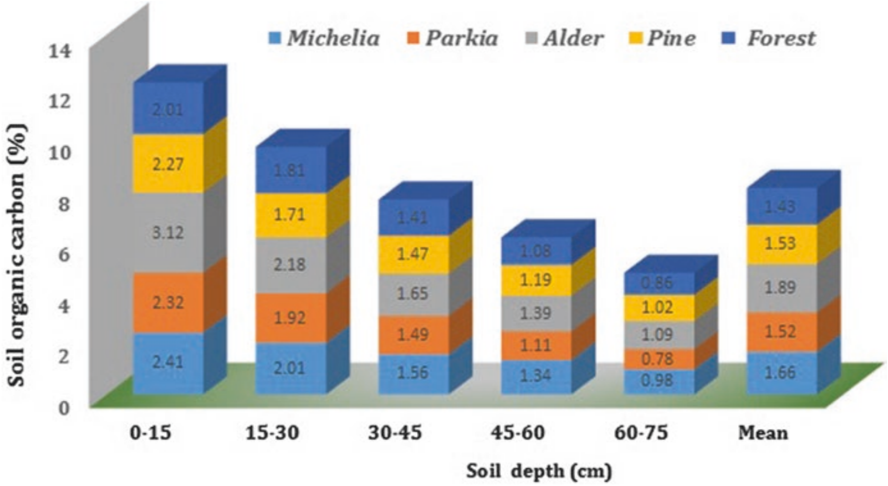


Fig. 11.6 Soil organic carbon (%) under different multipurpose tree species in the NEH (Source: Ramesh et al. 2013)

4 Influence of Soil Parameters on Carbon Stocks

Soil physicochemical properties play a major role in the soil carbon sequestration of agroforestry systems. These factors alter plant productivity and root growth and influence both the quantity and quality of litter and in turn affect the carbon dynamics in these systems (Ojima et al. 1991; Nair et al. 2010; Laganière et al. 2010; Cusack et al. 2009). Several studies (Kizito et al. 2006; Liste and White 2008) have shown that the hydraulic uplift of water by roots of a single tree will lead to an enhanced water uptake by neighboring plants as well in the agroforestry system which will in turn positively affect carbon sequestration by way of increased productivity and enhanced decomposition of carbon. Surface horizons of intensively managed agricultural landscapes are highly prone to erosion which will be reduced drastically by incorporating trees in the system (Lal 2005).

Trees will have a higher soil carbon sequestration potential than crop or pasture plant species as they help store more carbon in the relatively stable micro-sized (<53 μ) and macro-sized aggregates (53–250 μ) in agroforestry systems (Jobbágy and Jackson 2000; Nair et al. 2009b). Such organo-mineral complexes in these systems provide physical protection and biochemical recalcitrance to soil carbon and help to create a stable pool in these ecosystems. Studies by Mikutta et al. (2006) showed that most of recalcitrant carbon is bound in organo-mineral complexes in tree-based land uses; however, the formation of such complexes takes longer time to materialize (Six et al. 2000). Such aggregates protect SOC by (i) forming a physical barrier between carbon substrates and degradative forces in soil, (ii) controlling food web interactions, and (iii) influencing microbial turnovers (Fig. 11.7).

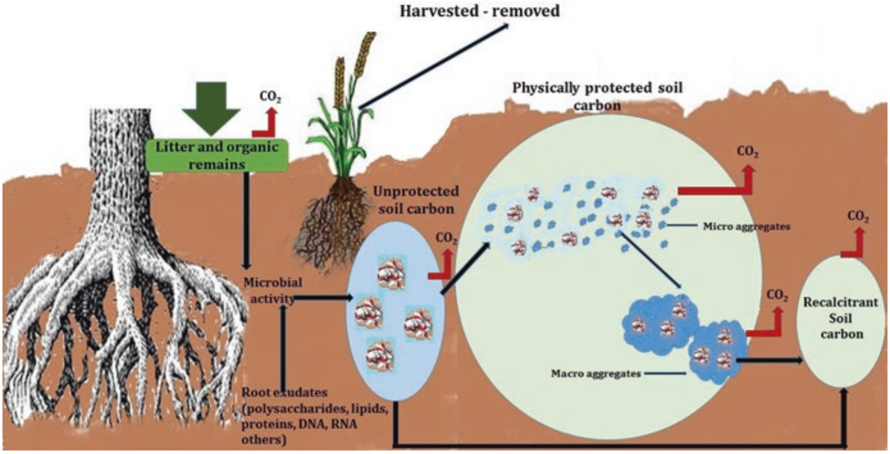


Fig. 11.7 Model of soil organic dynamics and stabilization under agroforestry systems

Agroforestry systems with long rotation periods generate a continuous flow of litter, and many of the compounds in fresh soil organic matter are protected by organo-mineral complexes or physically within the macroaggregate, but readily decompose when exposed. Thus, the process of carbon sequestration in these systems hinges to a large extent on the formation and stability of macroaggregates and availability of fresh soil organic matter.

The enhancement of microbial communities, their activities, and overall biodiversity under the tree species may also provide a favorable environment for greater SOC sequestration (Mitchell et al. 2010). However, field-based studies of such soil carbon processes and mechanisms in tree-based ecosystems such as agroforestry systems of NEH regions are scanty. Ecosystems such as agroforestry systems with high input of good-quality organic residues tend to have a high amount of soil microbial biomass and activities as these organic substrates provide microorganisms a ready source of energy (Hassink 1994). This in turn enhances the MBC and microbial biomass nitrogen (MBN) pools in these soils. A study by Ralte et al. (2005) shows that in North-East India, the presence of tree species (primary forests) enhances MBC pools when compared to *jhum* fallows, tea garden, and orange orchards. Hence, agroforestry systems which integrate trees along with crops can be expected to have a better soil carbon pool status than its agricultural crop alone counterparts.

Apart from the positive effects obtained by integrating trees into agricultural systems (Nair et al. 2010), there can also be several possible adverse interactions (e.g., pests, drought, fires, plant competition, etc.) which may lead to reduced tree performance and carbon sequestration in agroforestry systems (Burgess et al. 2004; Sileshi et al. 2007; Mosquera-Losada et al. 2010; Rigueiro-Rodríguez et al. 2009). SOC stocks represent a dynamic balance between organic material input and their decomposition losses and as such exist in a variety of carbon pools with a wide

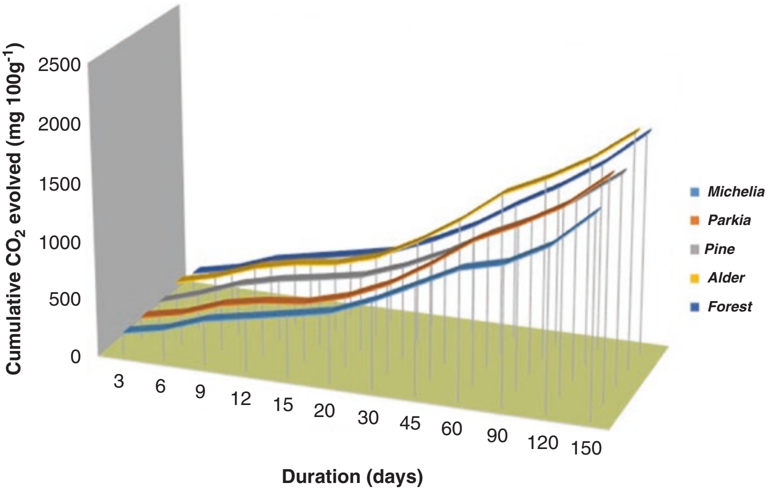


Fig. 11.8 Cumulative CO_2 efflux from soils of various multipurpose tree species at 35 °C in NEH region of India (Source: Ramesh et al. 2013)

range of mean residence times (Jenkinson and Rayner 1977; Saggar et al. 1994; Torn et al. 1997; Oelbermann et al. 2006). For example, non-woody plant materials and fresh litter are quickly decomposed and usually have a mean residence time of approximately 3–4 years. On the other hand, woody materials form a part of the passive SOC pool and persist for longer periods of 1000 years or more by way of their chemical inertness or physical protection rendered by soil (Parton et al. 1987).

Multipurpose tree species used in agroforestry systems of the NEH region were found to promote high CO_2 production with declining soil pH, wherein they promote H^+ release for cation uptake by plant, enhance litter accumulation, release organic acids from decaying organic matter, and increase root respiration (Tripathi et al. 2009; Yao et al. 2010; Ramesh et al. 2013). High biomass productivity and larger belowground carbon allocation by tree species lead to enhanced carbon source availability for biochemical decomposition and CO_2 releases from these systems (Fig. 11.8).

As such, there can be significant changes in this CO_2 efflux between tree species depending upon the soil parameters, litter fall rate, contribution from root biomass, chemical complexities of the added biomass, decomposition rate, and microbial community acclimatization to the prevailing environments (Chaudhary et al. 2009). Nevertheless, soil aggregation and ensuing physical and chemical protective mechanisms under such systems reduce the quantity of CO_2 released when compared to non-agroforestry practices. However, some authors argue that soil aggregation should be considered as a transitional soil property and would exert carbon protection only to a limited extend as the aggregates destroy and reform themselves constantly (Six et al. 2004; Kong et al. 2005; Sandeep and Manjaiah 2014). Hence under high temperature, there is a high chance that the physically protected SOC is exposed to degradation forces either by carbon desorption from adsorption sites (Hulscher and Cornelissen 1996) or by enhanced efficacy of enzymes (Reichstein et al. 2005).

Integration of crop production systems with trees and their management strategies will alter the rate and quantity of sequestered carbon (Nair et al. 2010). Soil management practices in agroforestry systems affect quality and amount of carbon inputs especially the belowground components (Nair et al. 2009b). In general, SOC accumulation in any agroforestry system is usually a complex mix of partially decomposed components, fire residues, and microbial end products rather than humic materials alone. Environmental factors help in physical disconnection, e.g., from organo-mineral associations, enzymatic decomposition, electron acceptors, and freezing/thawing that govern the SOC cycling (Schmidt et al. 2011). Carbon residues added to the surface get incorporated with the mineral matrix either by solubilization or by physical mixing or by transport and subsequent adsorption (Lorenz and Lal 2005). As plant roots act as the primary vector for most of the carbon (litter and rhizodeposition) entering the SOC pool within and outside the soil aggregates, the depth distribution of the tree species may be considered an important factor for carbon distribution and its long-term carbon storage in the soil profiles of the agroforestry systems (Rasse et al. 2005). However, there exists limited knowledge of carbon rhizodeposition by mixed plant communities such as agroforestry which hampers the rigorous quantification of carbon sequestration potential of these systems (Jones et al. 2009).

Dissolved organic carbon (DOC), though forms only a small portion of SOC, is a direct belowground carbon input (Bolan et al. 2011). The major sources of DOC in agroforestry systems include stemflow, through fall, humus, freshly deposited leaf litter, and crop residues as well as applied organic amendments. The subsoils of NEH being developed under a humid tropical climate are rich in amorphous iron and aluminum oxides and hydroxides and play a significant role in DOC retention. Thus, agroforestry systems with high contribution of DOC can contribute to their effective translocation and formation of mineral-bound SOC, a process that ensures carbon accumulation in the region (Bolan et al. 2011; Schrumpf et al. 2013).

Biotic and abiotic factors play a major role in carbon stabilization in an ecosystem. Though microbial-derived organic materials play a crucial role in carbon stability, the molecular complexities of the plant inputs as such have only a secondary role. Within a given soil environment, carbon stabilization can be perceived as a function of resource availability and microbial ecology. In general, processes which retard or physically exclude accessibility of carbon to decomposing forces and organo-mineral/organometal interactions can ensure long-term carbon stabilization in soils. Kögel-Knabner et al. (2008) noted that physical protection of organic carbon is essential for short-term carbon stabilization from decades to centuries, whereas organo-mineral complexes or organometal complexes are required for their long-term storage spanning centuries to millennia. Chemical composition-induced recalcitrance as well as physical protection will allow carbon fractions to sustain in soil sufficiently long enough to form stable organo-mineral complexes (Six et al. 2000). Agroforestry systems should focus on using suitable tree and crop combinations so that these sequences of processes are not disrupted and organic carbon exposed to decomposition (Ewing et al. 2006). In short, the sequestration of SOC in agroforestry systems can be summarized as a complex interaction of carbon with its environment vis-à-vis chemistry of the organic compound, soil minerals, climate, soil reaction and its redox state, water availability, and the microbial ecology in the soil microenvironment (Schmidt et al. 2011).

5 Management Strategies for Enhancing Carbon Storage in Agroforestry Systems

Soil carbon content in agroforestry systems can be enhanced by increased biomass additions along with reduction in their decomposition rates. The decomposition rates of SOC in these systems can be decreased by adopting measures that reduce water and nutrient losses and soil management strategies that enable physical, chemical, and biological mechanisms of carbon stabilization (Lal and Follett 2009). Like agricultural systems, reduction in cultivation intensity along with soil supplementation with mineral fertilizers, irrigation, and residue incorporation will lead to enhanced carbon sequestration in agroforestry systems (Nair et al. 2010).

Soil management strategies such as manure additions will influence the formation and stability of soil micro- and macro-sized aggregates in agroforestry systems, hence carbon stabilization and sequestration. However, the effects of fertilizers and herbicide applications have showed mixed effects on soil aggregation and carbon storage in these systems of the NEH region. The anthropogenic impacts on soil carbon sequestration through management practices can be achieved only to a certain extent. There is a limit for the carbon entering and stabilizing in a soil, and it has been noted that beyond a certain limit, carbon additions may not necessarily get incorporated into microaggregates, rather get added to the more labile macroaggregates that will be easily decomposed (Gulde et al. 2008). Hence the effects of improved management strategies on SOC contents in the agroforestry systems of the region can be considered highly site-specific.

Agroforestry systems with multiple species are reported to have greater potential than the best-performing monocultures in productivity and carbon sequestration due to increased belowground interactions (Ong et al. 2004). Agroforestry management for carbon sequestration should include aspects such as the selection of tree species, stand density, rotation length, and silvicultural management (Nair et al. 2009a). Studies by Saha et al. (2009) showed that the soil carbon stock (1 m depth) was directly related to plant diversity wherein smaller-sized homegardens had higher tree densities and could store up to 119.3 Mg ha^{-1} than larger-sized agroforestry systems (108.2 Mg ha^{-1}).

Tree species with extensive and deep root systems will have a higher carbon sequestration potential in the agroforestry system due to a high potential for carbon input into the system (Kell 2012; Lorenz and Lal 2010). For example, broadleaf trees have an extensive deeply anchored root system than coniferous trees and therefore generate higher carbon inputs from roots in the soil profile. However scanty reports exist on the ability of different agroforestry species and mixed plantations to store carbon in deeper mineral soils of NEH region (Jandl et al. 2007). In conclusion, comprehensive studies are required to assess whether these agroforestry systems can be manipulated specifically to maximize the soil carbon sequestration by exploring the sequestration potential of the entire soil profile in the presence of different tree species and their associated root-derived carbon inputs.

6 Conclusions

The traditional practice of agroforestry for achieving maximum resource use efficiency has recently received much interest and attention due to its potential for carbon sequestration and thereby climate change mitigation. Including woody perennials or trees specifically enhances climate benefits among other ecological benefits. Agroforestry systems in the NEH region promote soil carbon sequestration both by increased carbon inputs and enabling physical and chemical protection of added residues. Stability of the stored carbon can be summarized as function of its interaction with the environment that includes chemistry of the organic compound, soil minerals, climate, soil pH and its redox state, water availability, and microbial ecology. As existing reports on carbon storage potential and its decomposition losses from soils are highly variable, site-specific agroforestry management can be recommended only after gaining a comprehensive knowledge of the sequestration processes in soil profiles of the NEH region.

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Chapter 12
Silvopastoral Systems as a Tool for Territorial Sustainability and Biodiversity

F. Torres-Manso, A. A. Marta-Costa, M. Castro, and L. Tibério

Abstract Rural and livestock population evolution in the inner north of Portugal has demonstrated a great regression with consequences for environment and nature conservation. In this context, and taking into account that pastoral activity has shaped the natural areas of mountain territories since its beginning and that territories are currently part of Natura 2000 network, rethinking the importance of such activity has become vital. The constraints affecting daily tasks performed by shepherds and livestock breeders as well as the installed social segregation are a strong limitation. However, current research developed in the context of nature conservation has demonstrated the importance of the landscape mosaic promoted by grazing in the preservation of priority habitats. In this way, it is urgent to assess the issue of shepherds and livestock breeders' image in terms of their roles, relationships and concerns, as well as to assess pastoralism socioeconomics in regard to self-consumption, market and rural self-sufficiency. In this perspective, this work presents an analysis of the adaptation of grazing to current times, perceiving its limitations and success potential.

Keywords Grazing · Natura network · Shepherds · Socioeconomics

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1 Introduction

Since 1955 rural and livestock population show a decreasing evolution in Portugal (Torres-Manso et al. 2014). Such phenomenon, demonstrating the problem of rural abandonment in marginal areas, has originated an increase in moorlands and the development of large-scale shrub vegetation, therefore promoting combustible biomass accumulation which is intensely correlated with fire propagation. Several authors (Almeida and Moura 1992; Mather and Pereira 2006; Ruiz-Mirazo and Robles 2012; Mancilla-Leytón et al. 2013) have pointed out the existence of larger burnt areas in municipalities with a higher immigration degree, therefore highlighting that the relation between demography and fire incidence is stronger for forest stands than for rangelands. Consequently, there is an increase of burnt areas in regions with population loss, which are dominant in regions with the larger forest stand areas when compared with mountain regions, in which shrub areas are partitioned by meadows and small oakwoods, therefore promoting biodiversity (Torres-Manso et al. 2014). Extensive pastoralism remains in the latter landscape context, and its non-existence would jeopardise the heterogeneity of several priority habitats of Natura 2000 network. Current research in the scope of nature conservation has demonstrated the importance of the landscape mosaic promoted by grazing in the mentioned habitat conservation (Papanastasis et al. 1998; Mouquet et al. 2005; Whitehead et al. 2005; Pereira 2006).

The tendency for the decrease of pastoral activity has contributed to raise new questions regarding pastoralism relevance as an environmentally important socioeconomic activity. In the Portuguese mountain and/or inner areas, there are known conditions of isolation, the lack of accessibility and logistic infrastructures. Urban areas are therefore more attractive with expectations of a different, modern and socially prestigious life, with a higher availability of material assets. Likewise, it is known that many times, abandonment of rural areas is not only the outcome of economic issues but also of the social discredit of rural works. For some, isolation, rurality and tradition are associated with lagging or inexistent development and even to a reversal on the production process. Pastoral activity is still based on traditional ancient know-how and practices that not always follow commercial and financial market evolution. Thus, rethinking the issues of shepherds and livestock breeders' image in terms of their roles, relationships and concerns becomes crucial, as well as rethinking pastoralism socioeconomics regarding self-consumption, market and rural self-sufficiency.

In this perspective, a set of approaches have been made in the scope of Natura 2000 network and focused in mountain territories of the inner north of Portugal, with the goal of understanding contextual issues concerning extensive grazing, shepherd activity and its importance for nature conservation. In this sense, the framing of the Sites of Community Importance (SCI) which were the focus of the mentioned studies and the respective extensive grazing systems is made in the following section. Section 3 describes the relationship between the systems and shepherd activity, pointing out its constraints and highlighting its role in the scope of nature conservation. The analysis of socioeconomic sustainability of grazing systems and its current evolution and gradual adaptation to reality is presented in Sect. 4.

2 Sites of Community Importance in the North Interior of Portugal and Extensive Grazing Systems

Europe's most important international legal agreements for protected areas are the UN Convention on Biological Diversity and the EU's Birds (79/409/EEC) and Habitats (92/43/EEC) Directives (EEA 2012). These two nature directives are at the core of the continent-wide biodiversity conservation strategy, guided by the European Commission and implemented by the member states (European Commission 2014a and 2014b in Kukkala et al. 2016), and have established the Natura 2000 network of protected areas over Europe. Currently, there are more than 27,000 SCI, covering 18% of EU's land area (EEA 2012). These protected areas encompass a wide variety of natural environments, from the Black Sea shoreline to Alpine meadows and from arid shrubland to rich pasture (EEA 2012). In Portugal, Natura network comprises 61 sites and covers about 1,600,000 ha, i.e. about 20% of Portuguese mainland territory.

A great part of these protected areas in Mediterranean highlands of the north of Portugal underwent profound changes on their demographic structure, social organisation and usage of space by humans, since the middle of the twentieth century. These abandonment processes were preceded by an intense human intervention over the centuries, particularly those connected with pastoral activities. Because of this relationship, several grazing systems have been developed. Some of them are disappearing rapidly, but there are still fine examples, like the mountain regions of Portugal's inner.

This chapter addresses five mountainous SCI, located in the North inland of Portugal (Fig. 12.1). Regarding low population density and grazing systems, these SCI are very similar however their ecological differences. Specifically, it will focus on the "Douro Internacional" (plateau nature) and the "Montesinho-Nogueira", both with climatic continentally influence; the "Morais-Azibo" with a pronounced Mediterranean character; and the "Alvão-Marão" and "Serra de Montemuro", which present marked Atlantic nature.

The mountainous areas of northern Portugal overlap with regions tending to be depressed by adverse edaphoclimatic conditions and marginal rural areas, usually peripheral and difficult to access, either by orography or inland conditions. However, in these mountain complexes, the singular topography, soil heterogeneity and the range of slopes are factors that promote the high diversity of habitats and silvopastoral systems. Mountain pastures are an essential element in the creation of a number of mountain ecosystem services on which human wellbeing depends (Aguiar et al. 2015). Thus, water quality, landscape, biodiversity shelter, forest products,

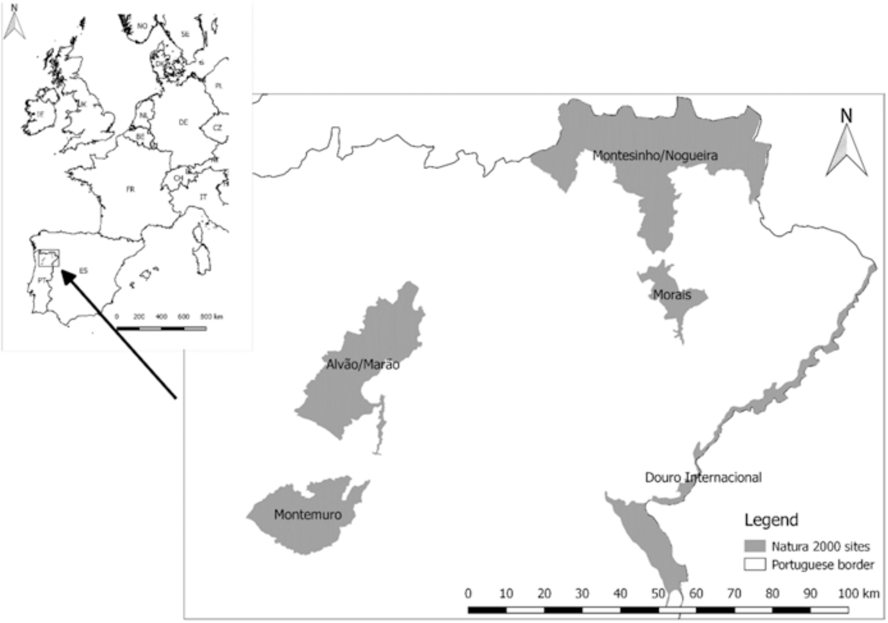


Fig. 12.1 Natura 2000 network studied SCI in the north of Portugal (Source: Own elaboration)

agriculture products and quality meat are examples of regulation and supply services. Poor soil suitability and altitude, both agricultural production limiting factors, allow little more than the practice of extensive shepherding which constitutes a primordial human activity from time immemorial.

Extensive grazing systems are normally associated with the constant demand for intrinsic regulations, e.g. low consumption of agronomic and/or veterinary inputs, use of native and rustic breeds, and use of trees and shrub species as fodder for animals, among others (Castro 2016). The nature of extensive systems relies on their resilience, i.e. in a demand for a proper production level that uses the least possible external resources, with special emphasis on the adaptation and farming of native breeds – a central element of extensive production systems. Likewise, it is worth pointing out that these systems are also an integral part of the territory's historic and cultural heritage (Telo da Gama 2004). Usually, there is a low animal density per area unit, and animal feeding is based on natural pasture. Pastures vary significantly over the year, both in availability and nutritional terms. Also, grazing activity is a unique exploitation mean for extended land areas, as it allows the concentration of scattered primary production and its conversion into animal protein sources. In these regions, small ruminants and beef cattle of native breeds, complemented by annual rainfed crops, are relevant and are the foundation of economic activity for these territories, as they often represent the last chance of landscape use.

In the larger part of these mountain regions, small ruminant production is based in the shepherding system (Castro et al. 2000), characterised by the daily travels of the flock, wandering through lands with no agricultural use, with feeding being based in a complex network of concentric paths that lead to the places where the flock stays overnight (Castro et al. 2003). Shepherding circuit planning is the outcome of an assessment of available land made by the shepherd in which he considers environmental and logistic constraints (Castro and Castro 2003). In these systems, animal grazing is made only in the territory of the parish or in its surroundings. The animals are kept in stables at night, and its location is a determinant factor for the definition of grazing itineraries, due to animal physical limitations.

Despite the current decline of pastoral activity, it is also worth highlighting the important meaning of extended marginal areas in shepherding, fundamentally, in route shepherding. Most of these areas are frequently community areas where there are low shrubs formed by heath (*Erica* spp.), *Pterospartium tridentatum*, gorse (*Ulex* spp.) and *Halimium* spp. (Torres-Manso 2015). These community areas, also designated as "common lands", can be used by any resident or breeder of the group of civil parishes to which the respective common properties belong. Over time, common lands became an important resource in terms of flock grazing, as community use has always favoured shepherding (Pinto 1999).

Depending on species demands and considering a scale of variation between sheep, goats and cattle, one can identify systems that predominantly use natural food resources, others that integrate agricultural by-products, stubble and fallow lands, and others associated with forage crops, focusing on animal feeding. In the case of cattle, the grazing system is more unmoving than in small ruminant, and it focuses on grasslands associated with other fodder crops which vary according to ecological conditions of the site. In the region, there are two broad types of grasslands which can be related to geology and soil type and, to a lesser degree, altitude and climatic conditions. Acidic grasslands normally occur on lighter sandy soils or in upland regions. Neutral grasslands occur on clay loams or alluvial floodplains, mostly lowland but some in upland situations. Concerning management types and water availability can occur hay-meadows or pasture and dry or wet meadows. In the Douro Internacional and Morais-Azibo SCI, the meadows tend to be less productive than in the Montesinho-Nogueira, Alvão-Marão and Montemuro SCI, due the drier climatic conditions associated with poor soil suitability.

Meadows are ecosystems with a special conservation status in Portugal, and their management is made in a very peculiar way that is also essential for their protection and for their potential productive in grass and hay. Four types can be distinguished, in function of water availability and management by the herders: dry hay meadows, dry pastures, wet hay meadows and mowing meadows.

Dry hay meadows are reserved between March/April and June (for highlands usually in late July), when they are harvested, and then they are grazed if there is pasture. Some of the dry meadows (dry pastures) are used only for grazing, which are usually those less wet and consequently less productive, sometimes designated as *pastigueiro*, depending on hay reserved and livestock farming demands (Sousa and Sanchéz 2009). Wet meadows are usually also undergoing a mixed-use regime, generally with two cuts, the first for grass and the second for hay (Sousa and Sanchéz 2009). Others, abundant in water and located near the parish, are destined only for

Table 12.1 Seasonal daily grazing durations and distances walked by goats and sheep (mean ± S.E.M.). Different letters indicate significant differences between seasons for the same animal species

	Daily grazing duration (min d^{-1})		Grazing itinerary length (km d^{-1})	
	Goats	Sheep	Goats	Sheep
Autumn	8.8 a ± 2.55	9.4 ± 1.75	7.02a ± 0.83	10.1a ± 0.58
Winter	5.8b ± 1.25	6.7b ± 1.25	6.14a ± 1.59	5.07b ± 2.68
Spring	6.5b ± 0.72	8.2ab ± 1.9	5.16a ± 0.85	4.00c ± 1.84
Summer	6.3b ± 1.98	9.4a ± 1.85	6.13 a ± 0.89	6.27b ± 3.48

Source: Castro and Fernández-Núñez (2016)

grass, therefore being designated as mowing meadows (Teles 1970; Portela 1988). These provide forage for complement cattle feeding when hay meadow which is shut off from grazing livestock. In the plateau of Miranda do Douro (Douro Internacional SCI), the most common forage is corn, unripe rye and oats, hay, usually ad libitum, and cereals (rye grain) only for exceptional feeding needs (cattle breeding and raising and cows postpartum) (Sousa and Sanchéz 2009).

Meadow lands are usually private property and are normally located near the village. Typically, the number of beef cattle in farms depends on the area of the private meadows. Shrub biomass consumption is significant, which, associated with goat headcounts, extends the fire reoccurrence cycle. On the other hand, common lands are in more remote areas and are used during summer, when lowland resources are scarce and daylight hours are sufficient to allow cattle to go to the mountains and return daily. Thus, beef cattle feeding in these areas is based on different quality pasture that depends on the season, with animals being supplemented with hay ad libitum during winter and with corn and rye flour being fed only to calves.

As for small ruminants, grazing itineraries are limited by natural factors like the daylight time, maximum and minimum temperatures, stable location and resource availability (Castro et al. 2009; Castro 2004). Resource availability and spatial distribution are also important factors, though not decisive for the itineraries, as the said aspects affect essentially the distance, given that animals take longer walks when food is scarce and smaller walks in the remaining cases. Table 12.1 shows seasonal variation of itinerary distance and duration for goats and sheep at Morais-Azibo SCI.

In the Morais-Azibo and Douro International SCI, climate conditions are more Mediterranean, affecting itinerary planning in a more significant way than in the remaining cases (Montesinho-Nogueira, Alvão-Marão and Montemuro). As sheep are very sensitive to high temperatures, in these hotter and drier areas, during summer, the flocks graze during the night. They set out to pasture before sunrise (between 4:00 a.m. and 5:30 a.m.) and remain in the fields only during the coldest period of the morning (they return to stables between 8:30 a.m. and 10:00 a.m.). Again, they graze at sunset (between 7:00 p.m. and 9:00 p.m.) for about 3–4 h. This is practiced during autumn until temperatures drop (Castro and Fernández-Núñez 2016).

Studies performed at Montesinho-Nogueira SCI have also found an important annual variation in itinerary duration (lengths) which correlates with maximum daylight duration (Castro et al. 2009). For goats, the variation between August and December was 12.4 and 6.35 h, respectively; for sheep, variation between July and December was 15.35 and 6 h (Castro 2004). Also at Alvão-Marão, SCI goat grazing itineraries were studied between August and October, and there were some variations found in the duration (6–9.5 h) and in the length (7.2–13.7 km) (Torres-Manso 2005).

The difference between daylight time and length of grazing itineraries suggests different patterns in goat and sheep requirements and management systems, showing sheep vulnerability to high temperatures. The length of sheep summer itineraries is higher than daylight time due to the long resting time during the hottest period of the day, being the only time of the year when sheep itineraries are longer than goat itineraries (Castro 2004). According to the same author, daylight time determines the duration of grazing itineraries, in both sheep and goat flocks. Nevertheless, the abundance of feeding resources and temperature pattern also play an important role in the duration of grazing itineraries.

3 Interactions Between Grazing, the Shepherd and Nature Conservation

Grazing systems are typical of mountain areas and are associated with livestock production based on sheep and goat native breeds. On their daily itineraries, flocks cross a variety of vegetation types, in different stages of their ecological succession, enjoying several food nutrient sources. This way, during the itinerary, animals can use natural or seminatural herbaceous plant communities, small-sized shrub communities, predominantly gorses (*Ulex* spp.), heaths (*Erica* spp.) and *Pterospartum tridentatum*, for more Continental-Atlantic locations, and laudanum (*Cistus ladanifer*) and rosemary (*Lavandula* spp.), for more Mediterranean locations.

Crossing different types of lands is made pursuant to unique rules and planning. The use of areas dominated by low shrubs is preferentially made by morning, while areas dominated by herbaceous plant vegetation or shrubs with younger sprouts are used preferentially in the evening. This pastoral planning is justified by the higher shrub vegetation freshness at early hours of the day, after a night period with higher levels of humidity and lower temperatures, and by the need to keep the flock well fed at the end of the day, so that animals can go through the night until the next day. It is worth mentioning that when the animals leave the stable in the morning, they have a greater appetite, therefore eating woodier material with lower nutritional values. Grazing itineraries are the result of the optimisation of several flock needs (feeding, rest, watering), structural variables (stable, water points and access location) and the land use restrictions (land interdiction due to municipal orders, ancient community rules, new forest plantations and temporary and permanent crops) (Castro 2008).

During the process of interaction between the flock and the lands explored by the animals, the shepherd is a core element in the proper exploitation and management of natural resources and, consequently, in the sustainability and rationality of the whole model that highly depends on him as a land manager (Castro 2016). The outcome of this process is a permanent animal-vegetation-man interaction. By shepherding his flock, the shepherd takes advantage of natural vegetation, therefore obtaining tradable products without incurring in high expenses for the acquisition of production factors. This way of living is a demanding and not very attractive activity, which consists in shepherding the flock in a daily basis, without holidays, weekends or vacation, therefore being subject to daily social isolation. This is often made under adverse climate conditions, mainly in the mountains during the winter, with his meals, made in the fields, consisting in food brought from home, before leaving. A specific knowledge becomes necessary to keep and direct a flock in the conditions this activity is practiced, i.e. the shepherd's own know-how, gained over many years of learning (Barbosa and Portela 1999). For instance, goats leave the stable every day, and, other than that, they enjoy walking long distances when grazing (Pinto 1999).

Many of the areas covered are usually common land, mainly in the case of SCI of Alvão-Marão and Montemuro, although many north-eastern interior locations, namely, for the Montesinho-Nogueira, Morais-Azibo and Douro International SCI, are private areas, where the shepherd enjoys consuetudinary rights or even uses proper lands. Diversity concerning property ownership and usage may impair proper grazing management, as well as influence shepherd's freedom of actions. Pacheco (2002) highlights the infeasibility of the use of fences in common lands due to the imminence of conflicts with common neighbours, in addition to the absolute need of the shepherd's presence due to the danger of wolf attacks. However, nowadays, in the face of rural depopulation, there is a higher availability and diversity of grazing areas and a lower number of neighbours who allow that, with a lower chance of conflict, certain common areas are fenced. Land abandonment by its owners allows that current shepherds, via rental, increase their exploitation area and respective flocks. This has brought an intensification of production systems and a clear loss on the importance of shepherding. On the other side, it is worth highlighting that land depopulation leads to the abandonment of this activity and grazing decrease, which is leading to the shrub encroachment, therefore facilitating predator attacks and increasing the risk of fire.

In addition to his extenuating routine, the shepherd was, in a recent past, a frequent victim of social segregation (Pinto 1999). Under these circumstances, it is normal that the pursuit of this activity has decreased almost until its disappearance. There is however those who call for its conservation, notwithstanding its importance in rural area usage, many times justified when facing the argumentation of the higher quality of life when compared to the city.

According to Ribeiro (1998, in Pinto 1999), the history of pastoral activity has had some ups and downs, with the former concerning to times of depression and social instability and the latter regarding the general progress of calm and ordered peace. Martinho (1978) has mentioned that, despite the tendency for the abandonment of the pastoralism, people returning from the former colonies in 1975 “got hold” of sheep in Serra da Estrela and so did ex-immigrants from France and Germany.

This scenario of silvopastoral abandonment is not exclusive of Portuguese inner lands but a national and European problem which must be permanently reflected in terms of Common Agricultural Policy decision suitability in specific political, social and economic contexts of certain rural territories. In this scope, the European Shepherds Network Declaration was signed in 2015 which counts with more than 50 organisations that represent shepherds in 17 European countries, from Arctic, Atlantic, Mediterranean and Black Seas and Netherlands to the Alpine mountains (European Pastoralists Assembly 2015). These represent different cultures and grazing systems and claim a set of common interests in terms of silvopastoral activity defence and conservation. Among others, the following needs are highlighted:

- Recognition and valorisation of their cultural and social identity;
- Valorisation of their status and importance in territory management and planning;
- Creation of measures to ensure fair prices for their products;
- Own labelling as a guarantee for quality brands;
- Inclusion and representation in Common Agricultural Policy decision-making moments.

Among other things, that document reveals that current European shepherds have the capacity to plan and claim the valorisation of their status and role in territory management, in contrast with the former inexistence of awareness among traditional shepherds.

It is worth pointing out one of the foundations in which this declaration is based and that consists essentially in raising shepherds’ awareness for their determining role in the scope of environment and nature conservation. According to them: “We protect the environment by preserving valued ecosystems where threatened plants and animals can survive, preventing the spread of shrubs and reducing the risk of fires. We use areas that are unsuited for and complementary to other forms of farming. Grazing helps store atmospheric carbon and mitigates climate change. We successfully manage natural resources, because we live from them, keeping them for future generations” (European Pastoralists Assembly 2015: 1).

The preservation of flora and fauna species and their habitats through grazing is important for the environment and nature conservation. It becomes clear that when landscapes are not protected against fires, their habitats and respective species are not either and carbon dioxide emissions rise. Torres-Manso et al. (2014) have shown that lands where grazing has significantly decreased or has almost disappeared are more vulnerable to fires.

In the mountain territories of Portugal’s north and centre inner, landscape used by extensive grazing includes several priority habitats protected by the different sectorial plans of Natura 2000 network. The conservation of many of these habitats is strictly connected to shepherding, as the mat grass (*Nardus stricta*), junipers (*Juniperus communis nana*), meadows with *Gentiana pneumonanthe* and red-billed choughs (*Pyrrhocorax pyrrhocorax*), among others.

Also, Mouquet et al. (2005) mention the importance of using periodical and moderate grazing strategies for the conservation of mountain meadows communities with *Gentiana pneumonanthe* and *Maculinea alcon*, an herbaceous plant and an Alcon blue butterfly, respectively, both classified as endangered species (IUCN 2014). However, these authors point out that intensive and continuous grazing may have an impact in the perpetuation of these species. According to Wallisdevries (2004), if the grazing intervention is not very intensive, the landscape heterogeneity promoted by the low pressure exerted by grazing may become a positive contribution to the perpetuation of *Gentiana pneumonanthe* and consequently of *Maculinea alcon*.

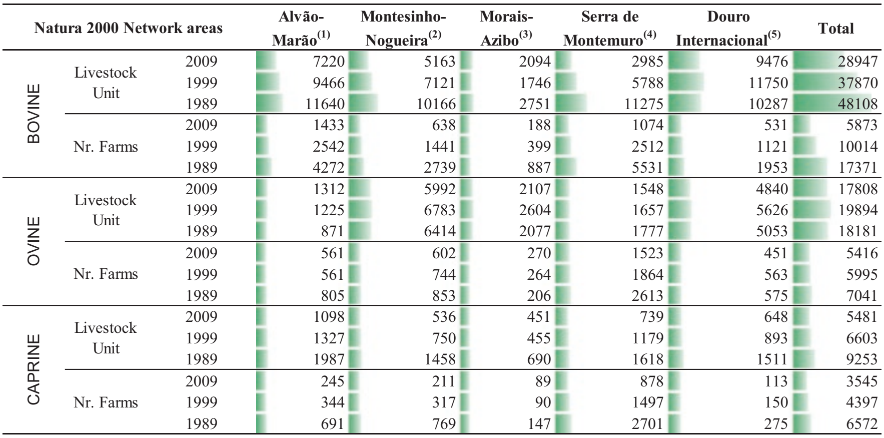
Pereira (2006) claims that the decline of the red-billed chough (*Pyrrhocorax pyrrhocorax* at the Natural Park of Alvão is essentially due to the abandonment of traditional extensive grazing systems. As its base diet is insects associated with livestock wastes, the abandonment of traditional grazing systems leads to the lack of concentrated food resources availability. Whitehead et al. 2005 have also shown the importance of partition promoted by selective grazing, given that wider areas facilitate the search for red-billed chough preys at the soil level.

According to Papanastasis et al. (1998), the long-term interaction between man and grazing in Mediterranean regions has promoted a remarkable contribution in the scope of ecosystem services, with the resilience to disturbances, fire prevention, biodiversity, hydrology and tourism being highlighted. The same author (2009) also mentions the role of grazing in ecosystem restoration, considering that proper management and handling may be a vital tool in silvopastoral areas, once these show an evolving trajectory from the presence of large herbivores to small ruminants. Thus, there is a degree of landscape modelling and species and habitat adaptability that must be considered and quantified from the decision-making point of view in the context of nature conservation measures.

4 Silvopastoral System Adaptation to Current Times

Native breeds of cattle, sheep and goats from the inner regions of north and centre of Portugal show a great affinity for classified areas, particularly for the territories specified in this study, with these integrating their farm of origin and current production areas. Despite the mutual relationships, animal headcount has decreased in the last decades as the number of farms, as confirmed in Fig. 12.2, following the decrease of the resident population (−8 to 2% between 2001 and 2014) and the aging index tendency (from 161.3 to 247.1, respectively) (INE, PORDATA n.d.).

In fact, this is a negative cycle dominated by a smaller and aging population and without qualifications reinforcing the lack of competitiveness of products gathered in farms with deficient size structure, where hard work is needed to overcome steep slopes and degraded or inaccessible trails for the herding. That situation contributes, in turn, to population decline and a further worsening of traditional silvopastoral system abandonment (European Parliament 2008; Torres-Manso et al. 2016).



Natura 2000 Network areas			Alvão-Marão(1)	Montesinho-Nogueira(2)	Morais-Azibo(3)	Serra de Montemuro(4)	Douro Internacional(5)	Total
BOVINE	Livestock Unit	2009	7220	5163	2094	2985	9476	28947
		1999	9466	7121	1746	5788	11750	37870
		1989	11640	10166	2751	11275	10287	48108
	Nr. Farms	2009	1433	638	188	1074	531	5873
		1999	2542	1441	399	2512	1121	10014
		1989	4272	2739	887	5531	1953	17371
OVINE	Livestock Unit	2009	1312	5992	2107	1548	4840	17808
		1999	1225	6783	2604	1657	5626	19894
		1989	871	6414	2077	1777	5053	18181
	Nr. Farms	2009	561	602	270	1523	451	5416
		1999	561	744	264	1864	563	5995
		1989	805	853	206	2613	575	7041
CAPRINE	Livestock Unit	2009	1098	536	451	739	648	5481
		1999	1327	750	455	1179	893	6603
		1989	1987	1458	690	1618	1511	9253
	Nr. Farms	2009	245	211	89	878	113	3545
		1999	344	317	90	1497	150	4397
		1989	691	769	147	2701	275	6572

Included municipalities: (1) Mondim de Basto, Vila Pouca de Aguiar, and Vila Real; (2) Bragança, and Vinhais; (3) Macedo de Cavaleiros; (4) Castro Daire, Cinfães, Lamego, Resende; (5) Freixo de Espada à Cinta, Miranda do Douro, and Mogadouro.

Fig. 12.2 Evolution of livestock units and number of farms of Natura 2000 network areas from the north of Portugal (Source of data: INE 2011)

Different strategies have been developed aiming the adaptation of cattle farming systems to current constraints. An example is the return to ancient practices like “vezeira” (the shepherd take all the flock to graze in a certain area in turns) and the introduction of “alternate shepherds” (flocks kept by different shepherds, in different time periods), in response to the lack of available labour. Areas distant from the farm, once shepherded and cultivated, were abandoned, as common lands whose distances are no longer walkable, therefore originating the need to obtain alternative food resources. Such resources are found in lands near residences – with many of these lands having been given for shrub control – or are purchased from external sources.

The use of factors in production that are external to the farm is bringing the grazing and extensive production systems closer to intensive livestock production, with consequent increase in production costs and profitability losses. The autonomy, typical of such traditional systems, is therefore somehow affected, having a negative impact in sustainability (Marta-Costa and Costa 2010).

According to several authors (Esquivel 1998; Masera et al. 2000; Marta-Costa 2010), the definition of a sustainable farming system is based on productivity, reliability, resilience, adaptability, equity and self-resilience, framed in the interaction between economic, social and environmental dimensions. The economic dimension of sustainability is important because it influences the activity’s survival and farmers’ permanence in rural areas which is essential for protecting the environment and preserving both the landscape and its natural resources (Masera et al. 2000; CEC 2001; Fernandes and Woodhouse 2008; Marta-Costa 2010; Marta-Costa and Costa 2010; Marta-Costa et al. 2012). In Table 12.2, some of the critical points negatively affecting sustainability of silvopastoral systems developed in the mountain areas of Portugal are summarised, which dominate the Natura 2000 network sites of the country.

Table 12.2 Critical points negatively affecting the silvopastoral systems sustainability of Natura 2000 network SCI of Portugal

Dimension		
Economical	Social	Environmental
Low system profitability	Absence of workforce	Lack of forest management
Low production efficiency	Laborious work	Forest abandonment
Very reduced livestock per farm	Lonely job	Predominance of non-native forest species in some areas
Subsidy-dependent systems	Population high aging rate	Villages dirty due to animal waste
No valorisation of farm products	Farmers low education levels	Absence of paths or inaccessible paths for the shepherd
Lack of monthly fixed salary	Absence of descendants to continue the activity	Evolution of used agricultural area occupation
Production input high prices	Low appreciation of agro-livestock social activity	Landscape in transition
Difficulties in selling products	High activity abandonment rates	
Lack of organisation of the entire row	Land structure (high fragmentation and steep slopes areas)	
Absence of accounting records	Poor housing conditions	
Low soil quality		

Source: Adapted from Marta-Costa et al. (2012) and Torres-Manso et al. (2016)

Despite the different ways of maintaining and adapting cattle farming, there are obvious consequences arising from current production techniques. Some of them include the biomass accumulation because of pastoralism decrease and changes in the occupation of the utilised agricultural area (UAA), which is evolving towards being gradually occupied by permanent pasture (Fig. 12.3). As a result, the landscape mosaic is changed with the promotion of landscape homogeneity which contributes to less biodiversity as pointed out in previous sections.

Social aspects imply changes in systems and in the surrounding environment, but there are other retrains from the economical point of view originating new contexts which promote paths to future systems (Fig. 12.4). Currently, there has been an increase in input prices and a constancy in output prices originating profitability loss and demotivation for the practice of this activity. Associated with this situation is the higher attractiveness of urban centres. Although the occasional phenomenon of "return to the fields" due to financial reasons, there is the need to develop some mechanisms capable of fixating economic activities in rural mountain areas and compensate its outputs. These activities support production systems required not only for food production and other raw materials but are also essential for ecosystems, biodiversity and landscape maintenance as well as to retain people in the territory and therefore prevent the increase of abandoned areas (Table 12.3).

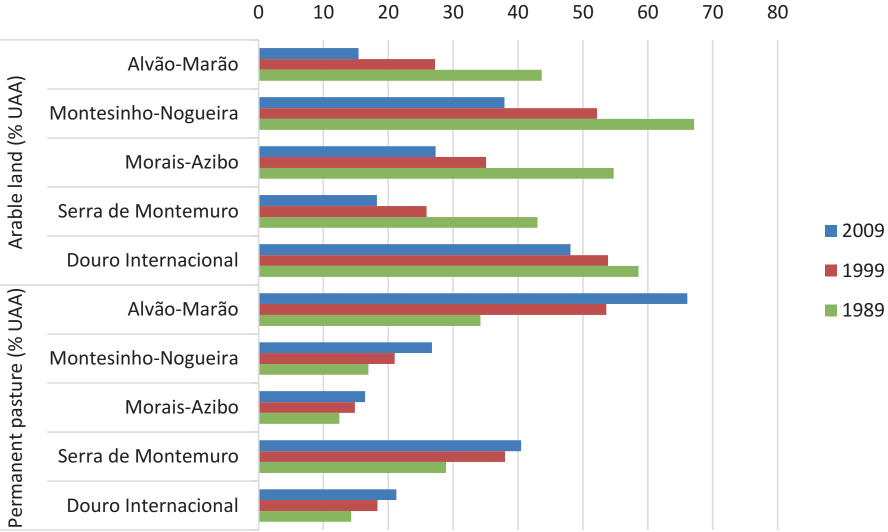


Fig. 12.3 Evolution of UAA occupation in studied Natura 2000 network areas, between 1989 and 2009 (Source of data: INE 2011)

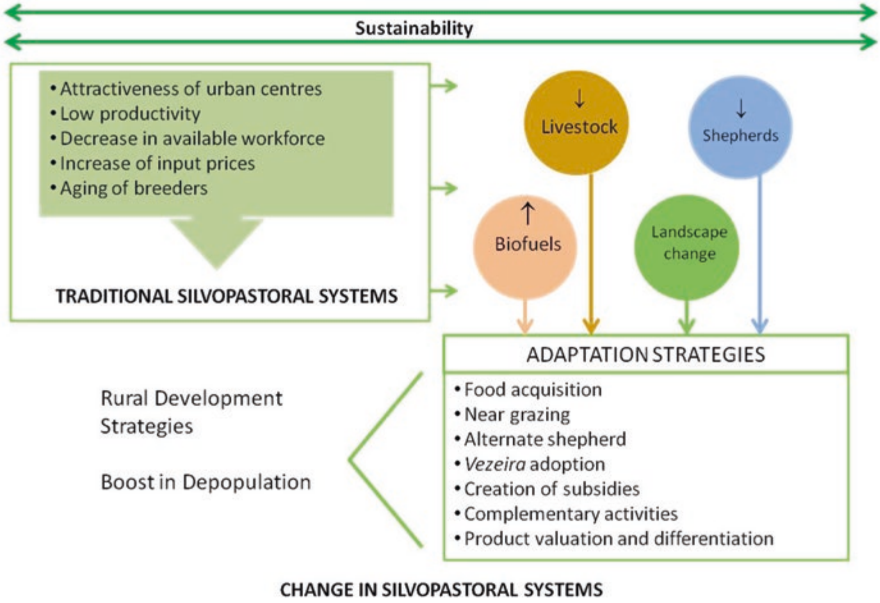


Fig. 12.4 Silvopastoral systems adaptation to current constraints for studied Natura 2000 network areas (Source: Own elaboration)

Table 12.3 Critical points positively affecting current silvopastoral systems sustainability of Natura 2000 network SCI of Portugal

Dimension		
Economical	Social	Environmental
Silvopastoral systems:	Silvopastoral systems:	Silvopastoral systems:
Are a main source of revenue for family farms	Allow self-employment creation	Contribute to the maintenance and valuation of areas with environmental interest
Produce high-quality certified products ensuring food safety health and hygiene standards	Allow to obtain food for self-consumption	Their several functionalities provide biodiversity and contribute to ecosystem conservation
Have low production costs due to the high rusticity of native breeds	Their products safe which provides a higher consumer trust level	Are fundamental to the conservation of indigenous breeds (some of which are endangered)
Have low (but growing) input dependence	Contribute to the maintenance of rural communities	Are based on rational agro-livestock management (better adaptation of agrarian activities to edaphoclimatic conditions)
Are based on farm's several functionalities	Provide wellbeing and better life quality	Reduce shrub encroachment and fire risk
Are supported by community measures		Contribute to the landscape mosaic
Contribute to valuation of abandoned areas		
Are an alternative economic activity		
Reduce costs on fire prevention		

Source: Adapted of Marta-Costa et al. (2012) and Torres-Manso et al. (2016)

In response and as part of agricultural or rural development policies, some measures for financial support have been developed and granted directly to farms by means of subsidies (agro-environmental measures, compensatory allowances and others). Other support measures focus on valuation and differentiation of obtained products, by making specific labels (PDO, Protected Designation of Origin; PGI, Protected Geographical Indication; TSG, Traditional Specialities Guaranteed; biological agriculture; production and integrated protection) originating increases in sale prices. Further measures have converged to the diversification of economic activities (different types of tourism, handicraft, innovation in market transformation and access), focusing on the complementarity of income sources to move into to more self-sufficient and viable systems in the long run. Thus, in many places, the effect of such practices is still not at the desired levels, not being sufficient to ensure positive evolutional trends for rural population and effective livestock in Portugal (Marta-Costa and Silva 2016).

There are however sufficient conditions to change practices in terms of traditional farming systems, focusing on their adaptation to environmental and socioeconomic impulses, when seeking and/or trying to maintain its sustainability (Fig. 12.4), reflecting themselves in the several territorial dimensions and its biodiversity.

5 Final Considerations

The classified mountain areas are geographically peripheral and difficult to access; moreover they have adverse edaphoclimatic and agroecological conditions and are in a disadvantage from a productive, economic and social point of view. However, over the centuries, human intervention through activities such as silvopastoralism shaped these areas to create habitats with high conservation interest. The negative evolution trend of the rural population and livestock population since the middle of the last century puts at risk the result of the mutually beneficial relationship between human presence, socioeconomic development of the territories and the preservation of the environment in rural areas. This situation is of specific relevance in classified areas of the Natura 2000 network, namely, in the SCI of Douro Internacional, Montesinho-Nogueira, Morais-Azibo, Alvão-Marão and Serra de Montemuro.

It is evident that the interaction between the shepherd, animal and the territory promotes benefits in landscape management and in the biodiversity conservation. This makes shepherds and pastoral systems that they implement real regulators and conservation agents, making evident the need to promote adaptations in the practiced production systems and within the associated ways of life, to make these activities more attractive, especially for the younger.

Different strategies, framed in policy measures, have been developed to reverse the downward trend of socioeconomic and environmental indicators in mountain areas both in general and in classified areas. However, its effects appear to be below from the desired, despite its contribution to the mitigation of the observed reality. At the same time, the natural adaptation of traditional silvopastoral systems to the new environmental and socioeconomic stimuli is aimed at seeking and/or trying to maintain its sustainability, reflecting themselves in the several territorial dimensions and its biodiversity.

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Chapter 13
Potentials of Poplar and *Eucalyptus* in Indian Agroforestry for Revolutionary Enhancement of Farm Productivity

K. S. Bangarwa and Chhavi Sirohi

Abstract Natural forest cover of India is declining, and timber imports are draining foreign exchange since the productivity aspects of forests have been assigned low priority in Indian policies. To overcome this problem, the forest trees should largely be planted on wastelands, which will help in sustainable timber and forest goods production. If the forest trees are used continuously and no replacement is done, forest trees will depart considerably by 2050, which will cause damage to the environment and biodiversity. Farm forestry/agroforestry offers the only tested technique to sustain the forest goods production and safeguard the integrity of natural forests. Quick-growing exotic species are of special significance when they are raised on agricultural holdings, mainly because they are capable to generate per unit more income than traditional agricultural crops. With this object, regular attempts have been made to successfully integrate the exotic tree species under various farm/agroforestry systems to increase productivity, thereby reducing the widening gap between demand and supply of forest products. *Eucalyptus* and *Populus* have played the revolutionary impact as agroforestry trees on farmers' fields, particularly in Indo-Gangetic Plains.

Keywords Agroforestry · Biodiversity · Exotic species · Productivity · Sustainable

1 Introduction

The total forest cover in India is estimated to 70.17 million hectares (Mha), which is 21.34% of the total geographical area (FSI 2015). Out of this, 8.59 Mha (2.61%) is very dense forest, 31.54 Mha (9.59%) is moderately dense and the rest 30.04 Mha (9.14%) is open forest. The trees outside forest (TOF) are estimated to cover

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9.26 Mha, which constitutes about 2.82% of the India's total geographical area; thus, the total forest and tree cover of the country is 79.42 Mha (24.16%). The country's forests have very low growing stock, i.e., 5768 million m^3, comprising 4195 million m^3 inside forest areas and 1573 million m^3 outside the recorded forest areas, which imply an average growing stock of 72.63 m^3 ha^{-1} in 79.42 Mha of forest and tree cover area (FSI 2015). With 2.5% of the total world's land area, India supports nearly 17% of the world's human population besides a large livestock population. Therefore, the forests are under intense biotic pressure, leading to degradation of forest resources. Forests have much lower growing stock (72.63 m^3 ha^{-1}) as compared to the world's average of 110 m^3 ha^{-1}. Likewise, the mean annual increment of forests in India is low (< 1 m^3 ha^{-1} yr^{-1}) as compared to the world's average of 2.1 m^3 ha^{-1} yr^{-1}. The condition of forest-based industries is very poor in India; thus, the promotion of large-scale farm or agroforestry plantation, which is essential in India, can be made possible through social forestry.

The National Commission on Agriculture first time used the term *social forestry* in 1976. Then, India embarked upon a social forestry project to take the pressure off on forests and made use of all fallow lands. Government forest areas that are close to human settlements have been degraded over the years due to human activities needed to be afforested. Trees were to be planted in and around agricultural fields. Planting of trees along railway lines, roadsides and on river and canal banks, village common lands, government wastelands and *Panchayat* lands was carried out. The National Forest Policy of India (1988) also directed the wood-based industrial units to meet their future raw material requirements through developing partnerships with farmers. Some progressive industrial units have promoted farm or agroforestry plantation through supply of planting stock, technical extension services and buyback arrangements. Short rotation tree species having faster growth, multiple uses and wider adaptability are desirable for agroforestry plantation. Agroforestry has expanded in the developing world due to forest scarcity, an increase in price of timber relative to grain and expansion of farming into land more marginal for annual crop production. It is a sleeping unit, which has tremendous potential for generating rural employment, meeting market demand for raw material for wood processing industries and all-round economic development. Agroforestry provides significant social, economic and environmental advantages, particularly in countries like India with subsistence agriculture, low and degraded forest cover and high deforestation rate. Agroforestry can improve the lives of resource-poor rural population by providing increased income, diversification and sustainability of agriculture and food security. It can also reduce pressure on natural forests and has a potential to bridge the gap in demand and supply of forest products, including pulp and paper. The supply of industrial wood from forest areas has been dwindling.

Trees outside forest (TOF) are the major source of wood for the Indian industry. Most of the wood-based industries like plywood and paper pulp are largely dependent on farm-grown wood rather than wood from natural forests and forest plantation. Huge volumes of logs, sawn timber, pulp and newsprint are being imported for meeting the growing domestic demand. Eventually, there is a great need to increase the area under tree cover and to improve the productivity. Substantial improvement in productivity of forest resources on sustainable basis and large-scale expansion of

Table 13.1 Demand and supply of wood (million m^3)

Particulars	1996	2001	2006	2010	2020
Wood demand for domestic furniture, agriculture and industries	64	73	82	95	153
Output from forests	12	12	12	12	12
Output from plantations (social and farm forestry)	41	47	53	58.5	88.7
Deficit	11	14	17	25.7	52.3

agroforestry plantation are important for meeting the national needs of timber and non-timber forest products, conserving the biodiversity-rich natural forests and achieving the national goal of 33% effective forest and tree cover. According to the National Agroforestry Policy 2014 of India, the national goal as desired tree cover from 25 to 33% in the country can only be achieved by planting trees on farm field/bunds, especially in states that have low tree cover. In fact, agroforestry has proven as an important tool for crop diversification. Forest-based industries in India show significant deficits between wood requirements and supply (Table 13.1). The rapid loss of natural forests in the country implies insufficient supply of forest resources to meet future needs. As a result, timber plantation, agroforestry and wood imports are supplementing India's demand for forest raw materials.

Tree farming is ecologically as well as economically more viable than traditional agriculture. Investment in tree plantation always remained relatively low in India although the existing forests cannot continue to meet the country's entire wood requirement. However, realizing the existing problems, the expenditure on afforestation has increased enormously from the fifth 5-year plan onwards, but the results on afforestation are still unsatisfactory since the area under forest as well as its productivity is not being increased to a desired level. The misery caused to the entire nation due to unprecedented eco-degradation is enormous and warrants immediate remedial measures. Presently, most of the industrial wood requirement was met from government-owned forests.

The National Forest Policy 1988 advocated moving towards a more dynamic program of converting the natural less productive forests into plantation of fast-growing exotic species, which are utilized to replace the local indigenous species that cannot produce the desired quantity and quality of products since the local species trees are not suitable for the purpose. To counteract the impending crisis, use of fast-growing tree species managed with intensive cultural operations especially in tree farming has opened new vistas in wood biomass production. The exotic tree species have attained a success, and many private concerns have initiated plantation activities. Exotic tree species have found their way into Indian farming systems since long. The need for introduction of exotic tree species arises either because the native tree flora is scanty or is chiefly composed of species, which are extremely slow growing and not readily available for use. Increasing productivity can reduce the widening gap between demand and supply of forest products. Introduction of fast-growing exotic species is necessary to increase the wood productivity of trees. Recently, the Supreme Court of India imposed the complete ban on green felling of trees. Now, the industries must meet their requirements from these trees grown on non-forestlands. Government forests are to be managed for ecological security and meeting the requirements of the local communities. With this change in policy, the exotic species, viz. *Populus deltoides*, *Eucalyptus tereticornis*, *Acacia mangium*, *Ceiba pentandra*, *Leucaena leucocephala*, *Gmelina arborea*, *Robinia pseudoacacia*, *Melia composita*, *Prosopis juliflora*, etc., which have established as good plantations, find more potential over the indigenous ones (Chauhan et al. 2008). However, *Populus deltoides* and *Eucalyptus tereticornis* are the two most important exotic tree species in India, which have been dealt here in detail.

2 Status of Poplar in India

Although poplar occupies a small geographical area at national level, it makes unique contribution to the socio-economy and ecology of regions of its occurrence. This tree was introduced from the United States of America in India in the 1950s. According to the Indian Council of Forestry Research and Education (ICFRE 2016) report, the area under poplar in India is estimated about 317,800 ha. The largest share (270,000 ha) is composed of *Populus deltoides* in agroforestry plantations (Table 13.2).

Table 13.2 Some important statistics about *Populus deltoides* in agroforestry in India

Area under pure poplar	317,800 ha
Poplar in forest area	47,800 ha
Poplar in agroforestry	270,000 ha
Exotic species of poplar	*P. deltoides*, *P. alba*, *P. euphratica*, *P. nigra* and *P. laurifolia*
Plantation region	Western Uttar Pradesh, Punjab, Haryana, low outer areas in Uttarakhand, Himachal Pradesh and Uttar Pradesh; recently introduced on a large scale by ICFRE in Vaishali district of Bihar
Rotation	6–8 years
MAI in farmers' field	20–25 m^3 ha^{-1} yr^{-1} in block plantations and 2–3 m^3 ha^{-1} yr^{-1} in boundary plantations
Soil and climate	Deep, fertile, irrigated, well-drained soil, subtropical climate and usually above 28°N latitude
Pattern of planting	60% plants as block plantation and 40% plants as boundary plantation; always planted with agricultural crops
Spacing	At 5 m × 4 m, 4 m × 4 m, 5 m × 5 m, 7 m × 3.5 m, 8 m × 3 m or 7 m × 3.5 m spacing as block plantation or at 2 m–4 m spacing in linear rows along the field boundaries
Combination crops	All grain, pulse and vegetable crops, except rice during *kharif* season; fewer crops can be intercropped in block plantations
Outturn	5.05 million mg yr^{-1} fresh wood
Returns/ha to grower	₹150,000 ha^{-1} yr^{-1} from poplar wood
Benefit-cost ratio	2.13:1 (with intercropping), 1.92:1 (without intercropping)
Utility	Plywood, board, match box, paper, charcoal, etc. (more than 30 products are made)

Source**:** Adapted from ICFRE Report 2016

The annual return from its cultivation is estimated to be around Indian rupees 2.5 million per ha per year. Timber from poplar is the backbone of vibrant plywood, board, match, paper and sports goods industries. Indigenous species of poplar are reared in forests as well as on private and government lands. Poplar has immensely contributed to the environmental and economic well-being of the state and reduced pressure on the forests.

2.1 WIMCO Role to Promote Poplar-based Agroforestry in Northern India with Special Reference to Haryana State

A major force behind the expansion of poplar-based agroforestry in northern India was a partnership agreement among a private matchbox-producing company, Wimco Ltd., farmers and financial institutions. To meet wood requirement of the state and to bring additional income to the farmers, poplar, which is a short rotation woody crop, was systemically introduced by WIMCO in Yamunanagar district of Haryana state in 1978 for growing as an agroforestry crop. In simple terms, the company markets a package to farmers targeted based on land suitability, which includes the supply of appropriate planting stock (2–3 m rooted sets of *P. deltoides* clones such as G3, G48, D121, S7CB, S7C15 and S7C20) and advise the stake holders on pit planting (5 m × 4 m or 6 m × 6 m), irrigation, pruning and management including intercropping procedures, but it was the buy-back arrangement of the farm forestry project, which was implemented by the Western India Matchbox Company Ltd., (WIMCO) from 1984 to 1990 that promoted the poplar-based agroforestry plantations. In this project, WIMCO used to enter into a buy-back agreement with the farmers to purchase poplars with girths above 90 cm at breast height. In this agreement, the company provided farmers with the option to sell their produce in the open market. At that time, majority of the farmers sold their produce in the open market because of high price of the wood, but the agreement was used only to build farmers' confidence during plantation establishment.

This buy-back agreement for National Bank for Agriculture and Rural Development (NABARD) was approved by the National Bank. Because of this agreement and the trees' multiple uses, farmers in northern India maintained the plantation of exotic poplar. Because of its ability to grow and mature quickly, poplar fitted very well into the commercial agroforestry system of Haryana. Cooperation extended by the government of Haryana through non-imposition of any restrictions on its harvesting, transportation and sale has encouraged farmers to take up poplar-based agroforestry (PBAF) on large scale.

2.2 Poplar in Indian Agroforestry

Poplar is one of the most preferred agroforestry species in irrigated fertile land in Punjab, Haryana, Western Uttar Pradesh and outer plains or valleys of Uttarakhand and Himachal Pradesh. It has gained considerable importance under agroforestry plantation, mainly due to its deciduous nature, fast-growing habit and adaptability to different environmental conditions and silvicultural systems. Genetically improved, true-to-type and uniform clonal planting stock of field-tested clones adaptable to specific sites has revolutionized productivity of plantations of poplars with major improvements in produce quality and profitability. This all enables the production of large quantity of wood in a short period of time. An area of nearly 270 thousand ha is under cultivation of poplar tree in various combinations with field, vegetable and fruit crops (ICFRE 2016). About 5.85 million of Mg fresh wood valued at ₹35 billion is annually produced in the country.

Plywood, board, matchbox, paper, charcoal, etc. are the major industries that consume poplar wood. Poplar provides huge cash returns to individuals engaged in its cultivation and industrial processing, contributes considerably to government exchequer, reduces pressure on forests and entails massive environmental benefits besides providing employment opportunities in transport, trade and various subsidiary sectors. The farmers in poplar-grown areas of the country have very conveniently adopted poplar-based agroforestry on farmlands. Technology-based innovative poplar agroforestry plantation models with genetically improved, high-yielding clonal poplars on farmlands have played an important role in India in meeting the growing needs of industrial timber on substantial basis, thereby saving precious forests. Poplar wood is suitable for various forest products, and poplar foliage provides a good source of fodder. In India, use of poplars in agroforestry has provided the highest internal rate of return and cost–benefit ratio as compared to other forest tree species. Poplar plantation outside the traditional forest areas offers tremendous potential for the enhancement of carbon stocks in developing countries.

2.3 Plantation Management

Poplar (*Populus deltoides*) is planted only in irrigated lands in northern Indian plains. Block plantations are raised by the farmers with large landholding. Owing to the existence of fewer risks and high profits in poplar cultivation, large farmers and absentee landlords prefer to put their lands under block plantations of poplar rather than pure agriculture or boundary plantation options. Usually, spacing of 5 m × 4 m or 4 m × 4 m (and sometimes 3.5 m × 3.5 m) is adopted. Small and marginal farmers plant poplar on field boundaries at about 3 m spacing between adjacent plants. Agricultural crops such as sugarcane, wheat, potato, mustard, maize, pulses, vegetables, fodder crops, medicinal plants, etc. are grown in the interspaces. Rice is not grown in block plantation of poplar. Pure poplar is seldom raised. If poplar is raised pure, the spacing is kept about 3 m × 3 m, and the stems remain thin, which fetches low price in the market. When poplar is planted on field boundaries, *kharif* as well as *rabi* crops can be grown in field throughout the rotation of poplar. In block plantation of poplar, the usual *kharif* crops can be grown for 2 years only; thereafter, the shade-bearing crops like ginger, turmeric, etc. are planted. However, *rabi* crops can be grown as usual.

2.4 Suitable Poplar-based Agroforestry Models

Poplar, a winter deciduous tree, is one such tree, which is being planted either in row, in crop fields, along field borders as boundary marker, or shelterbelts. Deciduous trees have considerable potential for integration into agroforestry, as they tend to use growth resources for only part of the year, thus, allowing resource use by adjacent or understorey pasture or crops to take place with minimal interference. Some of the important poplar-based agroforestry models being practiced in northern India are listed below:

- Poplar + wheat
- Poplar + mustard
- Poplar + sugarcane (initial 2 years)
- Poplar + turmeric
- Poplar + fodder crop

2.5 Intercropping with Poplar

Intercropping is almost always preferred as it provides scope for essential food production besides ensuring higher growth rate of poplar due to frequent irrigation and hoeing operations for agricultural crops. Dhiman and Chandra (2012) identified intercrops grown in poplar-based agroforestry and reported that around 98% of the poplar block plantation grow intercrops and only a few absentee land owners or casual growers avoid intercrops being grown. Research indicated that wheat to be the main crop could be grown in 51.67% cases followed by sugarcane, fodder, maize, pearl millet, sorghum, paddy, dhaincha (*Sesbania aculeata*) as green manure, etc. The intensity of cropping was more in winter (*rabi*) season than in summer (*kharif*) season. Farmers stopped growing intercrops much earlier in summer than in winter.

Sirohi et al. (2016) conducted an experiment to evaluate the performance of various wheat varieties under different spacings of poplar at the research farm of CCS Haryana Agricultural University, Hisar. They reported that maximum reduction in grain yield was found in wheat variety WH-1105 (59.2%) followed by HD-943

(48.7%), WH-542 (44.6%), DPW-621-50 (42.8%) and HD-2967 (27.9%). The best combination of spacing and variety under block plantation of poplar was 18 m × 2 m × 2 m (paired row planting) sown with HD-2967, which produced highest growth parameters like total tillers m^{-2} (331.4), number of earhead m^{-2} (324.3), number of grain/earhead (38.1), 1000 grain weight (38.2 g) and maximum grain yield Mg ha^{-1} (3.00). Among different wheat varieties, variety HD-2967 was found most suitable in poplar-based agroforestry system. In another study, it was reported that the age of poplar trees is the most important factor influencing grain (var. PBW 343) yield of intercropped wheat (Chauhan et al. 2009). On an average, reduction in grain yield was 20.10% under 1-year-old poplar plantation, which increased to 54% under 4-year-old plantation. Under irrigated poplar-based agroecosystem, light is the major limiting factor for reduction in grain yield.

Dhillon et al. (2009) conducted a study to explore the performance of turmeric under 3- and 4-year-old poplar canopy. Results showed maximum LAI of 0.52 and 0.44 under the 3- and 4-year-old poplar trees, respectively. Net photosynthesis, stomatal conductance, and transpiration in turmeric were higher in open areas than in shaded areas. The yield of turmeric under the canopy, though reduced, was not drastically reduced, and it was proportionately related to microenvironmental changes in light, temperature and humidity under canopy. It was suggested that to minimize resource competition and improve physiological processes of crops, such as turmeric, canopy management is essential to ensure better yield under poplar-based agroforestry system.

Intercropping of aromatic crops between rows of widely cultivated poplar with high-value medicinal and aromatic plants may provide a good opportunity to diversify agroforestry and increase the farm returns.

2.6 *Marketing of Poplar Wood*

Agroforestry is being promoted and popularized in India by the government and wood-based industries so that the requirement of fuelwood, fodder and timber wood for industries may be met from the farmers' field itself and the pressure on forests may be reduced. Selection of trees for agroforestry is of paramount importance from the viewpoint of promoting tree cultivation on farmers' fields. However, the development of agroforestry is facing certain barriers due to unorganized markets, poor technical and financial support and the lack of extension activities by the government, which must be addressed. Middlemen play a huge role in sale of poplar wood and often exploit the growers. The poplar-growing farmers face frequent fluctuations in prices of poplar logs, which was responsible for significant drop in planting levels of poplars during 2002–2004. At that time, shortage of poplar wood was soon felt in the market due to distress sale and removal of young plantations from field with virtually no replanting by farmers. As a result, the price started rising slowly in the late 2004. In December 2006, a high price of ₹600–650 per quintal (1 quintal = 100 kg) for oversized wood prevailed in the market. The price hovered above ₹1200 per quintal during 2012. It has now crashed to about ₹550 per quintal. The price of poplar wood in the market is extremely sensitive to lots of known and unknown forces. The availability of more supplies in north Bihar and adjoining areas after a couple of years from now is likely to have a noticeable impact on this situation. Poplar growers in that region are sceptical about the price they would get for their produce in the market.

Being a major raw material available to plywood industry of the region, it has sustained demand and market. The maximum production potential of a poplar plantation is 50 m^3 ha^{-1} $yr.^{-1}$, and the average potential of a poplar plantation is 20 m^3 ha^{-1} $yr.^{-1}$. Because of its deciduous nature, poplar can support the growth of agricultural crops beneath it without adversely affecting yield.

- During the first 2 years, the maximum returns can be obtained from a sugarcane + poplar combination.
- From the third year onwards, the shade-loving crops like turmeric and ginger can be grown successfully.
- During winter season, wheat can be grown.

With intensive management of poplar-based agroforestry models, the farmers are presently getting better financial returns than from other crop rotations. It has not only benefited the farmers but also has helped the wood-based industry and employment of various kinds. The scanty information available reflects the positive response in some crops and inverse trend with others when raised under varied tree canopies (Chauhan and Mangat 2006; Chauhan et al. 2007). Poplar-based agroforestry models whether block or boundary are popular in the irrigated agroecosystem throughout the northwestern states in India, with some region-wise variations in intercrops (Dogra et al. 2007; Chandra 2011).

2.7 Poplar-based Agroforestry in Northern India: A Case Study

In Yamunanagar district of Haryana, 79% of all planted trees are poplar, followed by eucalypts (19%). Wood produced from these plantations is now sustaining the raw material supply of hundreds of small- and medium-scale wood-based industries in northern India, manufacturing around three dozen products such as plywood, paper pulp, laminated board, packing cases, pencils, furniture and window frames. Lop and top and roots are used as firewood. Farmers have planted poplar in different designs (block, boundary and row planting), depending on their financial and technological capacity and management objectives. Usually, poplar trees are intercropped with agricultural crops like wheat (Fig. 13.1), sugarcane and shade-tolerant fodder crops like berseem (*Trifolium alexandrinum*) and sorghum. A financial cost–benefit analysis showed very favourable rates of return for the agroforestry production systems. The cost–benefit ratio of pure poplar plantations was 1:1:92 and 1:2:13 for poplar plantation with intercropping of agricultural crops. The higher returns of

Fig. 13.1 Poplar + wheat-based agroforestry system in Haryana

poplar with intercropping were due to mainly the higher productivity of the poplar trees in combination with agricultural crops. However, the farmers favoured poplar without intercropping, due to the better timber quality and the longer intervals between harvesting. The agroforestry production systems have brought about some significant socio-economic impacts. Agroforestry plantations contribute between 26% and 35% of local income, while agricultural crops contribute 34–60%. Further, agroforestry has improved the availability of fodder, which has led to a significant increase of milk production by 84% (Kumar and Rajput 2003).

2.8 *Income from Poplar Farming: A Case Study During 2016 in Yamunanagar, Haryana*

A progressive farmer named Thakur Singh who hails from Gondapura village of Saraswati Nagar Tehsil in Yamunanagar district of Haryana introduced poplar (G3 clone) for the first time in his farm during 1990 with the help of WIMCO under the scheme of buy-back arrangement. Under this scheme, supply of the planting material and total cost during plantation were provided by the company. However, timely irrigation, pruning, fertilizer and management including intercropping procedures was done by him with his own expenditure. Now he has a 100-acre (40.5 ha) farm in which he has grown suitable poplar clones WSL-110, WSL-109 and G 48 at a space of 5 m × 5 m. He said that poplars can produce moderate quality veneer logs at short rotation period of 6–8 years. At present the market of poplar is down, and it has now crashed to about ₹400 per quintal. The price of poplar wood in the market is extremely sensitive to lots of known and unknown forces. During 2014, he had sold 8 acres (3.2 ha) of poplar plantation (clone G48) worth ₹45 lakh (1 lakh = 100 thousand). Yamunanagar is the main market in northern India for wood-based industry (Fig. 13.2).

Fig. 13.2 Poplar wood industry in Yamunanagar, Haryana

2.9 Employment Generation and Upliftment of Rural Development Through Poplar Farming in Northern India

In the remote rural areas of Punjab, Haryana, Western Uttar Pradesh and Uttaranchal, smallholders grow poplar in agroforestry systems on fertile farmland. Poplar plays a significant role in rural development by generating employment to many categories of skilled, semi-skilled, and unskilled workers and thus helps in achieving the millennium goal of poverty alleviation laid down by the Food and Agriculture Organization. In the initial years of a plantation, the growing of agricultural crops together with the trees provides an immediate income. When the trees grow larger in size and the canopy closes, the crop yields decline. Poplar is grown over a rotation period of 8 years and produces peeler logs (75%), pulpwood (18%), roots and firewood (7%). Dhiman (2008) estimated 90–100 million man-days employment being generated from poplar activity in the country out of which 20 million man-days is in making and maintaining plantation; 20 million man-days in felling trees and their conversion into logs, grading, loading, unloading, stacking and handling timber; and approximately 50 million man-days in wood-based industry involved in converting poplar wood into wood-based products. Most of the operations involving poplar farming and utilization are in the remote rural areas where poplar is grown on farmlands and where employment opportunities rarely exist because of poor developmental activities in those areas. Poplar cultivation has become an important source of livelihood and prosperity, encouraging more and more farmers to grow poplar in agroforestry model.

Annually, about 50 million poplar trees are raised under agroforestry plantations in India, covering nearly 30,000 hectares and yielding 3.6 million cubic metres of wood every year. Thanks to India's 1988 National Forest Policy, most of the veneer, plywood and paper pulp units are now largely dependent on farm-grown poplars and other fast-growing species raised under agroforestry. It has been well understood that expansion of poplar agroforestry plantations is critically important to ensure abundant supply of raw material to wood-based units, improvement in livelihood security, carbon sequestration and overall socio-economic and environmental development. It is a viable option for the rural economy of India.

3 Status of Eucalypts in India

In India, vast areas of forested land have turned bare because of indiscriminate felling and exploitation. The problem has arisen when demand far exceeded the capacity of forest to supply wood without damage to the natural balance. It is not only the large forests that have been affected but small groves near villages, which helped meet needs of firewood and fodder, too, have vanished. A growing rural population with limited income opportunities and the related widespread rural poverty due to shrinking resource base have led to encroachment of forestlands. Diversion of forestland to non-forest uses (of the order of 150,000 ha annually) has also led to large-scale destruction of forests. It is estimated that of the 130 million ha of barren land in the country, 70–80 million ha is under private ownership. The success of agroforestry depends to a large extent on opportunities being taken up by large and small investors. There is a great demand of forest products for a diversity of uses, and the forest plantations, mainly established with eucalypts, are managed in rotations of different extent, being shorter for energy and pulp and much longer to obtain sawn wood. To supplement this demand, forest companies and farmers have been stimulated to cultivate eucalypts. The lands when developed carefully with various site-specific tree species for firewood, pulp and timber for various industries returns the green cover and can help change the picture completely in a few years. It seems reasonable to claim that, by providing the basis for a revolution in plantation economics, research-based clonal propagation has created new horizons for eucalypts in India.

The population of India is increasing at the rate of 2.78% per annum which means more houses are needed for shelter, fuelwood to warm and cook and clothes and paper. The industry requires raw material to manufacture the industrial quantities of consumables. Eucalypts are the only species like poplar which can be grown in the farmland to increase the production. Eucalypt planting in India started taking shape through extension activities of the state forest departments in the late 1960s and early 1970s. It gradually gained momentum in all parts of India, especially in Punjab, Haryana, Western Uttar Pradesh, Gujarat, Tamil Nadu, North Bengal and Andhra Pradesh. It was the most widely planted species in the foreign-aided social forestry projects of the 1980s in different states of India. In farm forestry component, eucalypts comprised 71.6% of the total trees planted. Though, the earliest adopters of eucalypts as a cash crop were the wealthiest farmers who had significant sources of off-farm income and who were seeking to minimize labour supervision requirements; it was soon adopted by the small and big farmers for production of small timber, poles, firewood and local house constructional material in the form of beams. With the course of time, eucalypts have changed the agricultural landscape

Table 13.3 Growing stock of eucalypts in trees outside forests

State	Growing stock of eucalypts outside forests (million m^3)	Total growing stock of trees outside forests (million m^3)	Percentage of eucalypts growing stock (million m^3)
Punjab	6.79	19.85	34.22
Haryana	3.83	14.44	26.50
Gujarat	14.98	47.78	31.36

of the states like Punjab and Haryana where monocultures of paddy and wheat berefted the soil of its nutrients and robbed off groundwater. Not only it has provided employment to the millions of agricultural labourers in the lean period but also yielded additional employment to the wood cutters, transporters and the industrialists. At present, eucalypts occupy the most predominant species in the *trees outside forests* (TOF) constituting from 12.10% to 23.72% of the total growing stock in any state (Table 13.3).

3.1 **Eucalyptus** *as an Agroforestry Tree Species*

Eucalypts are exotic to India, and the term 'agroforestry' is also new as it was introduced not more than half a century ago. Agroforestry systems for pulpwood production thus consist of growing of commercial timber trees for wood industry in agricultural fields with irrigation, fertilizers, plant management technology, etc., in a harvest cycle of 4–7 years. Crops growing underneath form a small part of the gross income. Selective shade-loving or shade-tolerant crops are grown to complement timber production and cash flow. As the trees must be grown on a quick rotation, the species selected should not only be fast growing but also suitable for combing with agriculture to maintain regular returns for farmers till harvest of the trees. Diversification of agriculture should receive very high priority as water resources are depleting and we are unable to arrange proper storage and distribution of huge stocks of food grains. However, tangible results can be achieved only if farmers are offered practical, viable and economically attractive alternative land-use options. Technology-based farm forestry plantations with genetically improved, high-yielding and fast-growing clonal planting stock of species like eucalypts have tremendous potential for diversification of agriculture and meeting growing shortages of industrial timber on sustainable basis. Eucalypts is one of the trees like poplar which can be grown with agricultural crops.

Eucalypts is the most popular choice to be planted along the edges, or bunds, of agricultural fields, and appears to be well incorporated and accepted in agroforestry in India (Tejwani 1994). Silvicultural properties including straightness, narrow crown, self-pruning, high growth rates, adaptability to a wide range of soils and climates, coppicing ability, a tendency not to spread as a weed and wide utility of wood are some of the main features of eucalypt clones making it popular among farmers for raising as block plantations. Eucalypts have more than 600 species, among which two species, *Eucalyptus camaldulensis* and *Eucalyptus tereticornis*, are cultivated more among the farming community in all over India, as being sufficiently drought tolerant while also capable of withstanding, under irrigation and saturation, very hot summer temperatures and suitable for a wide range of sites. The species were, of course, also selected because they are suitable for the manufacturing of quality paper.

3.2 Role of Private Sector in Promotion of Eucalypts Under Farm and Agroforestry

In farm or agroforestry programs where intensive cropping of forest species is undertaken, vegetative propagation of desired clones assumes still greater economic importance. Great benefits have accrued from clonal selection and breeding of eucalypts and from more intensive management practices, in which private sector has led the way in India. Fast-growing, high-yielding and disease-resistant clones of eucalypts popularly called as ‘Bhadrachalam clones’ have productivity of three to four times higher compared to the productivity of normal seed-based plantation (Lal 2000). Clonal eucalypt plantations, promoted, are the first successful example in India of commercial-scale clonal plantation of any forestry species traditionally propagated through seedlings.

Eucalypt plantation promoted by private companies receives generous incentives such as technical know-how for establishing the trees on the farmers’ land and contracts with the farmer to buy some or all of the first harvest for an agreed-upon price at the time of harvesting, sales tax exemptions on the pulpwood, procurement through agricultural market committees and no middleman involvement; hence farmer can sell his produces directly to the end users, and various tax holidays/exemptions for extended periods apart from the element of subsidies on the eucalypt clones are given by the company. These incentives put eucalypts at an advantage compared to other agricultural crops (including perennials), which receive no such promotion. Agroforestry is possibly the new alternative because of promising high returns. Farmers are willing to adopt clonal eucalypts under agroforestry plantations. This will serve the goals of sustaining the productivity of land, provide alternative agroforestry model to the farmers, increase the forest and tree cover in the state and conserve the water.

3.3 Spacing in Eucalypt-based Agroforestry System

Plant spacing is important to control the number and distribution of plants in the plantation area. In agroforestry plantations, optimum spacing should be compromised between the cultivation of crops as well as maximizing the production of wood and minimizing the costs of management and utilization. As a rule, when it is proposed to raise agricultural crops in conjunction with plantation, wider spacing should be adopted to protect the agricultural crops from shading as well as for free movement of agricultural machines. Moisture plays an important role in deciding the spacing in agroforestry plantation of eucalypts.

- Wider spacing is practiced in dry areas where soil moisture is the limiting factor.
- In irrigated plantations, closer spacing is adopted, as the cost for irrigation increases with wider spacing.
- In shallow soils unless fertilized, the spacing will also have to be wider for providing more spacing for root development.
- In wet areas, on the other hand, where ridges are prepared on drain ploughs, spacing has to be coordinated with the drainage pattern.
- Where there is a market for small-diameter stems, close spacing is usually adopted. Closer spacing can be adopted for production of fuelwood and small-diameter poles for pulpwood or pit props.
- When the main objective is to get the maximum production of saleable volume, closer spacing at short rotation helps.
- With wider spacings and short rotation, there is a loss of volume production since the site is not fully occupied and the mean tree size increases.
- The stem taper is also increased by wider spacing resulting in a reduction of the percentage conversion when the log is sawn.

Keeping in view the above principles in mind, the farmers have adopted the various spacings as per the realization of harvestable produce (Maithani and Sharma 1987). There are many combinations in agroforestry plantations. Putting plants 1 m apart in a row and keeping the distance between rows higher than this give higher yields in *Eucalyptus* hybrid plantation under agroforestry system (Table 13.4).

The most common practice adopted in irrigated agroforestry plantations is to have two-row strips, on a wider soil-worked ridge 1.5 m wide, 30–45 cm high, planting in a row at 1 m space. The distance between strips is kept 4 or 6 m depending on the cultivation practice. Another spacing that has become popular is 4 m × 2.5 m, wherein crops are cultivated up to the rotation period of 4 years.

Table 13.4 Recommended spacings for eucalypts under agroforestry

S. No.	Object of planting	Spacing (m)
1.	Firewood	1 m or 1.5 m apart
2.	Pulpwood and poles	2 m × 2 m or 3 m × 2 m
3.	Sawlogs	3 m × 3 m
4.	Windbreaks and shelterbelts	1 m or 1.5 m apart

3.4 Intercropping with Eucalypts

Intercropping is usually recommended for two reasons.

- The foremost reason is being that farmers care for trees when they care for crops.
- The second reason is being that regular irrigation and fertilizer application to crops benefit trees as well.

However, tree and crop management is required to make the system economically viable. As the intensity of shade increases year after year, there is a need to select appropriate shade-tolerant crops and standardized cultural practices that are complementary to each other. Of all the agroforestry systems that are being practiced, the adverse effects of single-row boundary plantation are minimum. Studies on the effect of boundary plantation of eucalypts on the yield of adjoining agriculture crops showed maximum yield reduction of 64.4, 58.4 and 42.6% in wheat, rice and potato crops, respectively, near the base of the tree line (Dhillon et al. 1979, 1982). The reduction in the yield is, however, dependent on the direction of tree line, its composition, spacing of trees, cropping season and type of agriculture crop cultivated. The minimum reduction in yield of crop sown on the southern side and maximum on the northern side of the tree line is also noticed. Another study on the effect of an 8-year-old eucalypt hybrid plantation in Dehradun on *kharif* maize crop found no significant reduction in yield because of moisture availability (Dadwal and Narain 1984). The results of still another study indicated that single-sided boundary plantations of eucalypts showed negligible adverse effects on wheat yield under irrigated conditions (Sharma and Unnikrishnan 2000). It can, therefore, be concluded that eucalypts grown on field boundaries do compete with agricultural crops for water, nutrients and light to varying degrees, thereby, affecting crop production. However, eucalypts when raised as windbreak or shelterbelt plantations under arid or semiarid conditions helped in increasing crop production. Low light intensity brings in decreased rates of photosynthesis under shade, affecting relative growth rate and reproductive and ripening phases of crops and, thus, ultimately leading to loss of yield.

Under certain tree canopy manipulation conditions and choice of suitable crops maturing at suitable spatial times can only help to work out an integrated approach for maximum production of tree and agricultural crop yields. Therefore, there is a need to identify the suitable agricultural and horticultural crops which can grow well along with tree plantation with limited solar energy availability. Some of the crops that can be grown in the *rabi* season include wheat, mustard, potato and fodders like *berseem* and oats that can be grown for the first 2–3 years depending upon the spacing and the intensity of shade. *Eucalyptus*–wheat-based agroforestry system is the most common practice in Indo-Gangetic Plains (Fig. 13.3), particularly in irrigated or waterlogged situations (Dagar et al. 2016). During *kharif* season, fodders like sorghum and pearl millet can be grown successfully after the first year of planting. Out of fodders, cowpea and pearl millet are reported to yield higher than sorghum during the initial 3–4 years. However, after the fourth year of plantation (4 m × 2 m), yield of these intercrops is negligible.

Fig. 13.3 *Eucalyptus* + wheat-based agroforestry system in Haryana

The effect of eucalypt on agricultural crops is not very well researched and needs to be thoroughly investigated. There are many interactions between the atmosphere, tree and agricultural crops both above and underground. There is a loss in agricultural production because of the shade covering the agricultural crops and competition for nutrients and soil moisture. The presence of trees changes the microclimate near the ground level by reducing the wind velocity, intercepting light and heat radiation and moisture. It is, generally, believed that agricultural crops and trees meet their nutrient requirements from different depths.

3.5 Economics of Eucalypt Plantations

In farms, where soil is well worked, deep and rich, eucalypts can give very high returns on investments. Economics of these plantations have been worked out by various workers in the past at suitable spacings and at appropriate rotations. The economic feasibility of *Eucalyptus* hybrid, with or without intercropping under varying spacings of 2.5 m × 2.5 m, 3 m × 1.5 m, 4 m × 2 m and 6 m × 1 m as practiced by farmers in Haryana, Punjab and Uttar Pradesh, was worked out (Mathur et al. 1984). The study concluded that for small farmers, planting of eucalypts on bunds is economically viable without sacrificing the agricultural crops. It was recommended that cultivation of eucalypts at wider spacing in combination with agricultural crops at 8 years of rotation ensures high economic returns. Similar views were expressed by Dogra (1984) that eucalypt plantations on agricultural farms proved to be highly economical giving an internal rate of return of 35–38% without intercropping and 85% with intercropping. It was concluded that on good agricultural land where irrigation is available, intercropping must be practiced since opportunity cost of this land is high.

3.6 Economics of Eucalypt-based Agroforestry Systems

The combination of agricultural crops with eucalypt trees for pulpwood production can bring a higher profit than pure planting of either. The profitability of eucalypt planting by individual farmers varies with the farm-gate prices and yields of the trees, which in turn depend on the quality of the soil, the spacing and the technology of production. The opportunity cost of the land is an important factor affecting the net return to the planters. High yields combined with better quality of produce and lower per unit production costs have improved profitability of clonal eucalypt plantation substantially. Because of better soils, adequate irrigation facilities and more progressive farmers, productivity of clonal eucalypt plantation is likely to establish new records. No wonder, therefore, that clonal farm forestry plantations of eucalypts are emerging as an attractive alternative land-use option offering tremendous opportunities for diversification of agriculture.

3.7 Marketing of Eucalypts in India

As compared to agricultural sector, the concept of marketing has not developed well in the forestry sector. Not much work has been done in India on the interrelationships between production levels and marketing of tree products. Eucalypt growers throughout the country sell their produce to the private traders at the lump sum price or based on weight. Very few farmers prefer to cut the trees themselves and bring the logs on their own transport to the nearby markets, where it is sold in auction by weight. The rates of wood in markets all over the country vary considerably in a season and also in different months in one particular season and also in different months at one particular place depending upon the quality as well as the demand of wood in the market.

At the time of harvesting of crops during *rabi* and *kharif* seasons, the arrival of wood in the market declines, whereas with the onset of winter season, the market shows upward trends due to increase in the demand of fuelwood as well as timber. Lack of efficient marketing system is believed to be the major factor in depressing returns from eucalypt plantation in Punjab and elsewhere (Negi et al. 1996). There is a decline in producer's share in consumer's rupee, with the increase in length of marketing chain. The existing marketing rules and customs also tend to complicate the marketing channels, and the middlemen take the advantages of the faulty market mechanism. There is no follow-up of the rigid rotations as the trees are felled as and when the need arises. Further, the harvest sales influence the postharvest sales to get competitive price in the regulated markets (Singh and Grover 1998). There is a need to educate the farmers by providing them the reasonable estimates of quantity and quality of wood in the standing trees through extension services. Some states like Haryana and Uttar Pradesh have set up forest corporations which purchase trees directly from farmers, but these purchases are estimated to about 0.1% of the total farm output of eucalypt trees. The types of sale (preharvest or postharvest) depend on many factors such as distance of timber markets from plantation sites, number of trees available for sale, area under plantation, cost of felling and transportation, availability of labour and market price of the produce. Farmers with small area under tree plantation mostly dispose of their trees in standing condition through contractors. The farmers away from markets preferred preharvest mode of sale as compared to the villages located near to timber markets due to high transportation costs.

4 Policy and Legal Framework for Poplar and Eucalypts

In India, poplar and eucalypts are largely grown by millions of small holders as block and boundary plantation under agroforestry. India has enacted the Indian Agroforestry Policy 2014, and the business rule on agroforestry program has now been vested with the Ministry of Agriculture and Farmers Welfare at central level and with the state agriculture departments at the state levels. India has also enacted Companies Act 2013 wherein each corporate body earning a net profit of over ₹50 million has to spend 2% of the profits under corporate social responsibility (CSR) in around one and a half dozen activities. Agroforestry has also been included in CSR activities during 2014, and some companies have started promoting poplar plantation on farmland under CSR activities (Dhiman 2015).

The Planning Commission of India (now *NITI Aayog*) has given a special grant to Punjab, Haryana and Uttar Pradesh states for diversification of agriculture where farmers are advised to move away from paddy cultivation to sustain agricultural production. Poplar and eucalypts are among the few trees promoted under this diversification plan. The saplings are largely procured from the private nurseries and supplied free of costs to the farmers. The process of allowing establishment of new wood-based industry and expansion of industry is now vested with the states. This decision was taken during 2015, when prices of poplar wood crashed and after a lot of representations from the growers, the Central Empowered Committee, which earlier was supervising this aspect at national level, gave the powers to the states. The Ministry of Environment, Forest and Climate Change will supervise the process. Some changes have also occurred in the procedure of granting felling and transit permission in the state of Uttar Pradesh. The tree growers till these provisions were required to apply manually to the forest department for felling and transit of trees. Poplar growers in certain districts of the states required permission of the forest department for transportation of their produce to wood markets. The new system requires obtaining revenue document showing growing of trees to be supplied to the divisional forest officer who lodges the document on the e-web created for this purpose, and the permission is granted by the state forest department. However, the procedure remains time- and resource consuming and has yet not eased the problems of the tree growers.

5 Impediments of Poplar and Eucalypts in Agroforestry

- There are practically no restrictions on growing, felling and transportation of exotic species such as poplar and eucalypts. However, there is a need to extensively review policy, rules, and regulations in respect of indigenous poplar and seedling eucalypts to rationalize the same with a view to encouraging their plantation.
- Most of the farmers are planting eucalypts at various spacings without knowing the silvicultural or economical aspects of planting under agroforestry. Even after half a century of eucalypts planting in the field, package and practices are widely under developed or unknown to the farmers.
- Institutional support and technical backup is required to promote cultivation of poplar and eucalypts.
- There is no regulatory mechanism to ensure supply of certified nursery stock/planting material to the growers. Certification mechanism backed by appropriate legislation is required to be put in place to check sale of physically or genetically inferior stock.
- Unlike agricultural crops, facility of minimum support price for wood of poplar and eucalypts, or any other agroforestry species, is not provided by the government. This leads to exploitation of growers. The fall in price of poplar wood in the past significantly reduced the interest of farmers in poplar cultivation. Similar mechanism as for agricultural crops or other institutional measures for assuring a minimum price to the growers of poplar wood is required.
- Providing facility of credit and insurance, as is available in case of traditional agricultural crops, needs to be extended to cover tree cropping.
- Flow of research grants from users (industries, farmers, forest corporations, etc.) to research institutions is absent, and the same needs to be initiated. This has been in vogue in agriculture sector in India since long. There is considerable need to focus on training and extension efforts in poplar and eucalyptus cultivation.

The following measures are suggested to overcome the above problems:

- Development of package of practices for different agroclimatic zones of the country including correct choice of species/clones, spacings to be adopted, cultural practices, rotation, yield expectation, and economics. Field testing of clones for identification of site-specific clones with high adaptability and productivity is required.
- Interaction of agricultural crops and trees and manipulation of canopies of trees toward the shade effect must be studied.

- Trials on new varieties of agricultural crops suitable for growing under partial shade must be conducted.
- Quality control and certification of planting material must be at place.
- Facilitating open auction of wood from farmland.
- Strengthening of extension wing of forest departments.
- Development of agroforestry cooperatives.
- Development of alternative uses of poplar and eucalyptus wood.
- Rationalization of transit rules.
- Regulating timber import under open general licence (OGL).
- Removing licence system on setting up of peeling and plywood units.
- Establishing more plywood units in different areas to absorb increased supply of poplar wood, etc. A healthy buyer-seller linkage is crucial for development of a sustainable agroforestry-industry model.

6 Conclusion

Technology-based farm forestry plantation of fast-growing exotic tree species like poplar and eucalypts has tremendous potential for supplementing agricultural production and meeting the growing shortages of industrial timber on sustainable basis. Farm and agroforestry plantation of exotic trees can take intense biotic pressures off the natural forests and help conserve their rich biodiversity. The self-sufficiency can be achieved in timber and wood-based products and can generate exportable surplus of value-added wood products over a period of time in the future. As we have inputs in plenty-ample sunshine, land for raising plantation and labour and scientific knowledge, we have definite comparative advantage in production of industrial timber and in marketing and export of value-added wood-based products if we adopt constructive and innovative policies. That will create ample employment opportunities for the rural poor and promote sustainable development of wood-based industries bringing prosperity to the states through multiplier effect. Thus, fast-growing exotic species, supported with sound silvicultural management practices and marketing support, can contribute immensely to meeting the demand for wood and wood-based products on a sustainable basis. Innovative policies for promoting integrated development of technology-based plantations and wood-based industries can create vast employment opportunities through local value addition, save scarce foreign exchange, and indirectly conserve our biodiversity-rich forests.

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Chapter 14
Biodiversity Conservation in Dryland Parkland Agroforestry Practice: A Review

Hintsa Muruts and Emiru Birhane

Abstract The conservation of biodiversity has been mostly understood in terms of the management of protected areas and natural forests, ignoring the possible role of farm areas and the ways through which dryland communities have promoted biodiversity in their agroforestry system and/or practices. Dryland biodiversity have developed unique strategies to cope with low and erratic rainfall. They are highly resilient and recover quickly from existing disturbances against risks such as drought, disease, and crop failure. These attributes have great significance for the global system, especially in the context of climate change. Dryland people have adapted many agroforestry systems and/or practices, which help them to conserve biodiversity and improve their livelihood.

This paper presents a review of dryland parkland agroforestry as a means for biodiversity conservation and explores options for its conservation and sustainable management. Findings of the review can be summarized as follows: (1) Dryland farmers maintain high levels of biodiversity in their parkland agroforestry. (2) However, dryland parklands are rapidly degrading over vast areas due to unsustainable policies and land management practices, causing negative impacts on both human well-being and the environment. Once these areas were the main source of livelihood, now they are becoming barren and unproductive. (3) In conclusion, the document identifies further research and intervention for promoting sustainable management of dryland parkland agroforestry as a means to conserve biodiversity.

Keywords Parkland agroforestry · Conservation of biodiversity · Dryland biodiversity

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1 Introduction

Agriculture of the future must meet the triple challenge of raising food production per unit area, reducing the vulnerability of agricultural systems to climate change, and reducing greenhouse gas emissions from agriculture (Neufeldt et al. 2009). Agroforestry system and/or practice is ideally placed to tackle all of the three challenges. There is a long tradition of agroforestry practice in many parts of the world involving combined production of trees and agricultural crops on the same piece of land. The intimate combination of such components with one another is an ancient practice that farmers have used throughout the world.

Parklands as agroforestry are landscapes in which mature trees occur scattered in cultivated/pasture or recently fallowed fields. Some of these trees were left when the forest was originally cleared; others regenerated after the land was cleared or were actively planted by farmers (Harvey and Haber 1999). In the ICRAF Agroforestry Systems Inventory, parkland agroforestry (PAF) is included in the very general category of “multipurpose trees on farmlands.” Growing and/or planting of multipurpose trees provides fodder for animals, ameliorates microclimate of the area, and reduces degradation of drylands through addition of organic matter and nutrients to the soil. Parklands have been also referred to as a vegetation type similar to “tree savannas” but differ from these in that they are of specifically human origin, with the composition and density of their woody component manipulated in order to facilitate its use (Boffa 1999).

The process of parkland agroforestry establishment relies on traditional agricultural practices which include selective clearing of natural vegetation and retaining only desired woody species on the land when establishing crop fields (Nikiema et al. 2005). The deliberate retention of different tree and shrub species for various purposes is common in many parkland agroforestry practices. There are different spacing patterns and densities of placement depending on the type of tree chosen and the type of crop grown, but trees are generally planted and managed at least 8–10 m apart and often much further apart (HDRA 2001). The spacing could be wide up to 20 m for wide canopy trees such as *Faidherbia albida*.

Parklands are common in dryland tropics particularly in Africa. It is widely practiced in the drylands of the western part of Africa, often with *Sorghum bicolor* (Sorghum) as major crop. In this cropping system with livestock as important component, trees are preserved in a naturally established, non-systematic pattern with relatively low tree density (Boffa 1999). In Burkina Faso, tree density varies from farm to farm and was usually between 15 and 30 trees per hectare (Kessler and Boni 1991). In Zimbabwe, Campbell et al. (1991) observed scattered trees in the fields with similar appearance and purpose. They also noted parkland agroforestry practices in Malawi and South Africa. In Mali, for example, parklands occupy approximately 90% of the agricultural land (Kalinganire et al. 2007). Parkland agroforestry practice is also common in different parts of Ethiopia. Traditional parkland agroforestry practiced for centuries in Ethiopia particularly in the southern part of the country (Zebene 2003). For example, *Cordia africana* is intercropped with maize in

Bako and western Ethiopia; *Faidherbia albida*-based agroforestry in the Hararghe highlands and Debrezeit area (Poschen 1986; Hoekstra et al. 1990; Badege and Abdu 2003). It is also common to observe parkland agroforestry systems that integrate *Faidherbia albida* trees haphazardly mixed with different crops and other tree and/or woody species in the central and northern part of Ethiopia. However, dryland parklands are rapidly degrading over vast areas due to unsustainable policies and land management practices, causing negative impacts on both human well-being and the environment.

2 Dryland Parklands Agroforestry and Biodiversity Conservation

Loss of biodiversity are being driven, mainly by human interference reinforced by inappropriate economic structures and activities that maximize short-term gain, without considering long-term consequences (Raven 2002). Habitat destruction by humans becomes the primary source for loss of species (Lugo 1988). The destruction could be both temporal and spatial and could encompass both in the natural and man-made ecosystem such as in agriculture and agroforestry.

Parklands generally incorporate several agroforestry tree species. Although frequently dominated by just one or a few species, parklands include a large number of woody species, often up to 40–50 in the cultivation cycle alone (FAO 1999). Most parkland species have a wide distribution range, occurring either in very localized or continuous patterns. They are, therefore, a very biodiverse agroecosystems with a high potential for biodiversity conservation. The parkland agroforestry practices have been described as good examples of traditional land use systems and biodiversity management practices (Boffa 1999). Remnant woody species in parkland agroforestry may play an important role in conserving biodiversity within farming systems because they provide habitats and resources that are otherwise absent from agricultural landscapes (Harvey and Haber 1999). They serve as critical nesting, feeding, and resting sites for a variety of bird and bat species. They also provide transient habitats for many migratory birds (Harvey and Haber 1999). The presence of woody species in parkland agroforestry favors the survival of native forest plants. In addition, parkland trees often serve as a source of propagules for forest regeneration both because they produce seed locally and because the birds that visit their canopies restate seeds of forest plants while perched in the trees. As a result, the seed rain beneath parkland trees is significantly higher than in open areas (Harvey and Haber 1999).

Some parklands are monospecific (e.g., *Faidherbia albida* and *Borassus aethiopum*-based parklands), but others have some dominant tree species mixed with a range of other tree and shrub species. Nikiema et al. (2005) recorded *Vitellaria paradoxa*, *Balanites aegyptiaca*, *Sclerocarya birrea*, *Bombax costatum*, *Lannea microcarpa*, *Sterculia setigera*, and *Parkia biglobosa* in Burkina Faso parklands.

Augusseau et al. (2006) and Ouinsavi and Sokpon (2008) recorded, respectively, 50 tree species in agroforestry parklands of the subhumid part of Burkina Faso and 45 species in *Milicia excelsa* (Welw) C.C. Berg agroforestry parklands in Benin. Fifanou et al. (2011) identified 21 tree species that belong to 14 botanical families during the surveys in Pendjari Biosphere Reserve in Benin.

A study from Sidama, Ethiopia, by Zebene (2003) showed that the higher number of species at Hara may be attributable to its late stage of agricultural intensification, and the associated higher number of native remnant trees, particularly in places with relatively remote access to market. In PLAF practice of Tutiti *kebele*, *Syzygium guineense* trees were deliberately preserved and managed on crop fields grown with annual crops such as *teff*, maize, barley, haricot bean, bean, and sweet potato. The number of *Syzygium guineense* trees preserved per hectare was on average 30 (Yeshimbet 2011). PLAF like the one in Tutiti *kebele* is common across the highlands of Ethiopia (e.g., Poschen 1986; Tolera et al. 2008; Abera 2009; Hailemariam et al. 2010). Most farming systems in the highlands host large tree stems of different species that are deliberately left and managed by farmers. For instance, in Tigray region Northern Ethiopia, Hailemariam et al. (2010) noted a PLAF practice where *Balanites aegyptiaca* tree was grown in association with sorghum. Abera (2009) also noted a PLAF practice where *Croton macrostachyus* followed by *Warburgia ugandensis*, *Syzygium guineense*, *Cordia africana*, *Pygeum africanum*, *Ficus vasta*, *Faurre arochetiana*, *Strychnos mitis*, *Podocarpus falcatus*, and *Olea africana* were grown in association with annual crops such as *teff*, maize, sorghum, and haricot bean by the farmers of Burkitu Peasant Association in Oromia region of Ethiopia.

Trees generally occur in low density, for example, 2–3 trees ha^{-1} in the case of large trees such as néré, 5–10 trees ha^{-1} in the case of karité, 5–50 trees ha^{-1} in the case of *Faidherbia*, and 10–45 trees ha^{-1} in the case of *Prosopis* (Rao et al.1998) and 1–20 trees ha^{-1} (Badege and Abdu 2003) to minimize impacts on the companion crop. Farmers' objectives for maintaining trees in these systems are to provide products such as fodder, fruits, and fuel wood and to reduce risk (Rao et al. 1998).

Parkland trees and shrubs provide many diversity functions for the rural poor. They are sources of food, including fruits, fats, oils, leafy vegetables, nuts, etc., which complement stable food crops in the local diet. Some of these foods are particularly important during the months when grains are in short supply and during years of intense drought (Kalinganire et al. 2007). In addition, parkland trees and shrubs provide numerous traditional medicines that are essential for rural health care. Severe micronutrient deficiencies can be alleviated by consuming indigenous fruits and vegetables (Ruel et al. 2005). They also supply fuel wood, construction materials, cordage, dyes, and materials for household implements, handicrafts, and clothing. Moreover, since the PAF is an essential source of forage, fodder, and medicines for livestock, tending healthy PAF is essential for maintaining healthy animal herds (Kalinganire et al. 2007).

3 Management of Trees to Increase Biodiversity in Parkland Agroforestry

For the normal growth, survival, and propagation of trees, farmers have their own knowledge about the management of the tree components found in parkland agroforestry practices. Different parkland tree species management activities are practiced in the dryland PLAF practice. Pollarding, lopping side branches, felling, and coppicing are the major traditional management practices followed by the local farmers to promote normal growth of the trees and to control its interaction with crops. The total lifetime contribution of a tree which is used in this way can be considerably greater than the volume it will produce if it is simply allowed to grow and is then cut down (FAO 1985).

3.1 Assisted Tree Regeneration

The composition of the tree component of these systems results from a careful selection over the generations resulting in what are called agroforestry parklands. Because of the high cost of tree planting, there is increased interest in the protection and stimulation of natural tree regeneration where mother trees are available (Boffa 1999). Natural regeneration has various advantages. For example, in comparison to tree planting, natural regeneration in dry zones of the Sahel with relatively low cost has the advantage of providing relatively short-term (2–3 years) benefits (Taylor and Rands 1991). In Dori, Burkina Faso, 90% of all dominant parkland trees are regenerated naturally rather than planted (ICRAF 1996). However, the physiognomy of the parklands is at present quite alarming because of lack of regeneration, which is explained by the shortening or suppression of the fallow period. This change in the land use system over time is likely to persist along with a growing population pressure on agricultural land and therefore requires urgent attention. The lack of natural regeneration inhibits the dynamism of the system to bring in new species to the system and could develop into a natural monoculture system that lacks diversity. Conservation and management of the parklands therefore needs a new approach which can turn some of the threats into sustainable management opportunities.

3.2 Planting

Traditionally, parkland tree species which easily regenerate naturally are not planted. However, the importance of planting as a technique for parkland establishment and regeneration depends on parkland tree species (Boffa 1999). For instance, in Wolokonto, Southwestern Burkina Faso, *Borassus aethiopum* parkland trees are believed to have been planted originally, even though the species is locally present in natural stands (Cassou et al. 1997). On the Seno plain of Dogon country in Mali, Sidibe et al. (1996) also observed that *Adansonia digitata* trees are planted in compounds and nurtured before they are transplanted along the edge of cultivated fields. Diversity of parkland systems could be enhanced through enrichment planting when the dynamics of the natural regeneration favors a monoculture system.

3.3 Pruning

Canopy of a tree may suppress ground vegetation; therefore, pruning (cutting back certain branches) of *Parkia biglobosa* is common and it was practiced on 10–30% of all *Parkia* trees in 21 villages on a north-south transect in Central Burkina Faso (Osman et al. 2011; Bayala et al. 2002). This practice is common to many other tree species in the parkland agroforestry system in the tropics. Farmers are used to the practice, but it needs a concerted effort in providing training and develops a package on pruning mechanisms to increase the diversity of the system. In Tigray farmers usually exercise intensive tree management such as lopping and pruning to regulate the height and canopy of *F. albida*. Repeated pruning during periods of average biomass production stimulates leaf production. It can be pruned twice a year. Resulting regrowth is especially vigorous in the first year but decreases as exploitation continues; trees show stress at the end of the sixth year. Regular lopping (once every 3–4 years) removing 0.4–0.5m^3 of foliage (or 35% of the total volume) at the start of the growing season is recommended. However, improper methods of lopping have been observed to cause wounds, predisposing the tree to attack by pathogens. The tree responds well to coppicing.

3.4 Lopping

Lopping is the pruning of smaller branches and twigs, often for fodder. It is a commonly practiced management activity in the parklands. In Southern Burkina Faso, lower branches up to 15 cm diameter have been cut off at their base in 56% of a large sample of *Vitellaria paradoxa* trees to allow maneuvering of draft animals and/or improve tree form to produce understorey crops (Boffa 1999). This practice is common in *Faidherbia albida*-based parkland system. It supports the regeneration of subordinate and suppressed species through the reduction of the canopy species.

3.5 Coppicing and Pollarding

Coppicing is to cut stem of tree and shrub at the base of the tree and shrub and pollarding is to cut the stem of tree/shrubs at 1.5–2 m height. These are common management practices in the PLAF practice. For example, in case study of the Upper Niger River Valley regions of Mali, Grigsby and Force (1993) observed when women were conducting coppicing activities for naturally regenerating trees on 3–5 years rotations to obtain diameters equivalent to the size of a fist.

4 Conclusion and Implications

Parkland agroforestry plays a crucial role in dryland biodiversity conservation. However, changing circumstances (climatic, political, among others) are threatening the efficacy and sustainability of these systems due to livestock pressure on seedlings that reduces natural regeneration, shortened periods of fallow, and severe tree lopping for feed requirements and firewood supply (Gonzalez and Tucker 2012). The exact nature and significance of the different constraints will vary depending on the specific geographical and social context. Understanding of the exact nature of constraints as well as rural people's needs and priorities is a precondition for sustainability of the parkland systems.

The sustainability of the parkland agroforestry is under serious threat of degradation because of accelerated changes in agricultural practices, as a consequence of increased demand for arable land, and the multiple function of the parkland system can only be fulfilled if parkland species diversity is adequately managed (Nikiema et al. 2005). Hence, trees improved through modern domestication methods may increase farmers' interest in maintaining and expanding their investment in parkland agroforestry. This requires tree planting but not strongly rooted practice in dryland areas.

Dryland agroforestry has a vital role in natural resources conservation and attaining food security in the arid and semiarid regions. Trees in the farming system have been playing a buffering role to the pressure on the remnant forests and providing products and services that are lost due to deforestation. Hence, dryland agroforestry is an important strategy to enhance natural resources conservation, improve productivity, and attain food security in the drylands. To harness the values of dryland agroforestry, strategic placement of trees in the farming system and appropriate management are important. This will help to maximize resources utilization, ensure positive companion interaction, provide diversity of products and services, attain producers' objective, and ensure sustainability and stability. Tree retaining from existing natural vegetation and maintaining tree from natural regeneration and tree planting in farms is a cultural practice that has been inherited from generation. A large diversity of tree species is being planted, retained, and maintained in farms in different spatial and temporal arrangements for different purposes at varied scale. These practices are also common across the different agroecologies. These agroforestry practices provide diverse products and services to the communities who are practicing them. The agroforestry systems that are being practiced by different community in different agroecologies have different species composition, spatial and temporal arrangement, different companion, extent, and management for different purposes.

However, the details of these agroforestry systems and practices have not been well identified, characterized, and appreciated. The tree species composition and the spatial and temporal arrangement of the different agroforestry systems and the ecological and economic interaction with companion species need further investigation. Likewise, the indigenous management practices for different purposes and the socioeconomic and ecological importance of different agroforestry practices are not well recognized and appreciated. As a result, the attempt to scale up and sustain some of the best indigenous agroforestry practices suitable to the agroecological condition is limited.

Future research and intervention on dryland parkland agroforestry need prior concentration on (1) assessing drivers of changes in parkland agroforestry practice (2) the adaptation of the agroforestry parkland systems to climate change, and variability needs a sufficient level of understanding of the system, its components, and their interactions, (3) incorporates new concepts of integrated ecosystem management and sustainable development, and (4) strengthens the scientific base of assessment and policy development work.

Researchers could focus on localized niches of increasing management intensity, where demand for germplasm is active. Biocarbon projects can connect climate finance to smallholder farmers and can provide considerable benefits to improved productivity, land health and income, market access, institutional stability, and, ultimately, food security and reduced poverty for asset—poor rural dryland communities.

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Chapter 15
Agroforestry for Increasing Farm Productivity in Water-stressed Ecologies

M. L. Soni, V. Subbulakshmi, K. R. Sheetal, N. D. Yadava, and Jagdish C. Dagar

Abstract Water-scarcity is increasing in many countries, and more regions are moving into increasing water-stressed conditions. According to an estimate, about 4500 $\mathrm{km}^3\ \mathrm{year}^{-1}$ more water will be needed to feed the world population in 2050 at current crop water productivity levels. There is little scope to increase food production by increasing the area under cultivation. Hence, there is a need to devise such production systems that can produce food from marginal agricultural land and is also capable of maintaining and improving quality of soil and environment. This can be achieved through agroforestry. In India, the current area under agroforestry is estimated as 25.32 million hectares (m ha). There is further scope of increasing the area under agroforestry by another 28.0 m ha in the future. Thus, a total of 53.32 m ha area of the country could potentially be brought under agroforestry in the near future, which will make agroforestry a major land use activity, after agriculture (140.86 m ha) and forestry (69.63 m ha). There is substantial experimental evidence to support the hypothesis that agroforestry may increase productivity by making better use of available resources. Significant complementarities of water use may occur naturally if trees with suitable leafing phenology or rooting architecture are used in agroforestry systems. To achieve this, the trees and crops must capture a greater proportion of the available resources and use them more efficiently to produce dry matter than equivalent sole stands. A number of technologies with suitable tree and crop combinations have been identified for different agroecological zones of the country. These technologies provide options for improving livelihood, environmental and energy security. This paper describes the promising agroforestry systems to achieve higher productivity in water-stressed ecologies.

Keywords Agroforestry · Water productivity · Water-stressed areas · Resource capture · Microclimate

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1 Introduction

Water is the scarcest commodity in dry regions. The growing population, rising incomes and climate change further limit its availability for food grain production and threaten food security in many countries. According to an estimate, about 4500 km^3 $year^{-1}$ more water will be needed from the current estimate of 7000 km^3 $year^{-1}$, to feed the world population in 2050 at current crop water productivity levels (Falkenmark et al. 2009; Rockstrom et al. 2009). This is more than twice the current consumptive water use in irrigation. Water-stress is increasing in many countries, and more regions are moving into increasing water-stressed conditions. Although the global amount of fresh water has not changed, the amount available per person is much less than it was in 1950, with significant regional and country level differences. Among the regions that are conventionally (blue) water scarce, but still have sufficient green (soil moisture used in rainfed cropping and natural vegetation) and blue water to meet the water demand for food production, are large parts of sub-Saharan Africa, India and China. If green water (on current agricultural land) for food production is included, per capita water availability in countries such as Uganda, Ethiopia, Eritrea, Morocco and Algeria will be more than doubles or triples. Moreover, low ratios of transpiration to evapotranspiration (T/ET) in countries such as Bangladesh, Pakistan, India and China indicate high potential for increasing water productivity through vapour shift (Rockstrom et al. 2009). The global assessment of green and blue water suggests that water-stress is primarily a blue water issue, and large opportunities are still possible in the management of rainfed areas, i.e. the green water resources in the landscape (Rockstrom et al. 2009).

Globally, the fresh water is about 2.5% of the total available waters, while the salt water accounts for about 97.5% (Shiklamanov 1990). Beneath many of the world's deserts, the aquifers are of saline water. The major occurrences are in the Thar Desert of India and Pakistan, the Arabian Desert of the Middle East countries, the Sahara Desert in North Africa, the Kalahari Desert in Southern Africa, the Atacama Desert in South America, the California Desert in North America and the West Australian desert. To use saline water for irrigation, one needs to understand how saline or sodic water affects the plant, what causes salinity in soils and waters and what levels of salinity are acceptable and monitor salinity levels to ensure they stay within the acceptable range and participatory resource appraisal, and one needs to be prepared to accept lower than average crop yields. Many arid and semiarid regions of the world have demonstrated large amount of saline groundwater, which have been successfully used to irrigate many annual crops (Tanji 1990) and agroforestry systems (Dagar et al. 2016).

2 Water-scarce Regions

World Resource Institute (WRI) scored and ranked future water-stress in 167 countries by 2040 (Fig. 15.1). Figure 15.1 shows the average exposure of water users in each country to baseline water-stress and the ratio of total withdrawals to total

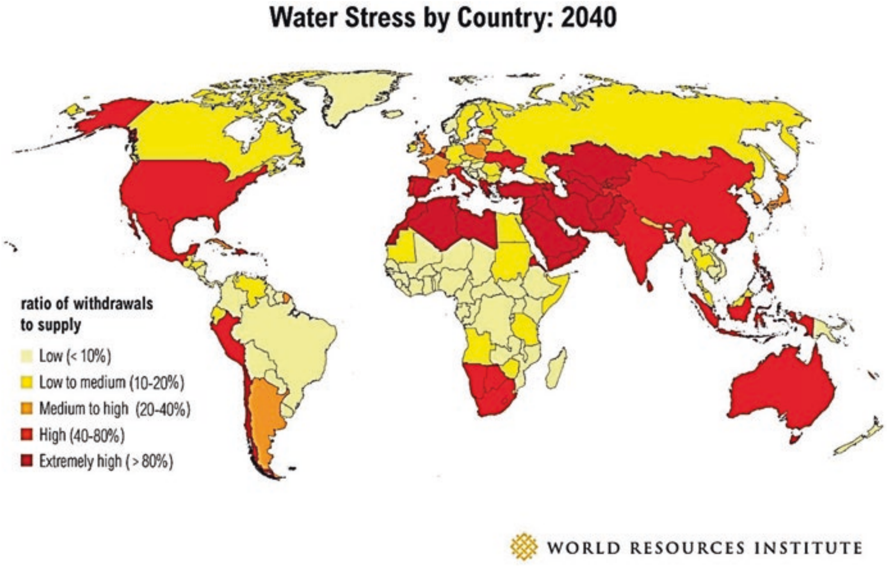

Fig. 15.1 Water-stress in different countries by 2040 (Source: Luo et al. 2015)

renewable supply in a given area. A higher percentage means more water users are competing for limited water supplies. It is expected that about 33 countries will face extremely high water-stress in 2040. Fourteen of the thirty-three countries will likely be the most water-stressed countries in 2040 including nine countries considered extremely highly stressed, mostly situated in the Middle East (Bahrain, Kuwait, Palestine, Qatar, United Arab Emirates, Israel, Saudi Arabia, Oman and Lebanon). The region, which is already the least water-secure in the world, draws heavily upon groundwater and desalinated sea water and faces exceptional water-related challenges for the foreseeable future.

Arid and semiarid regions with high population densities (such as parts of India, China and the Middle East/North Africa (MENA) region) are facing absolute water-scarcity. The MENA region is increasingly unable to produce the food required for its population due to increasing water-stress from a combination of population increase, economic development and climate change and will have to rely more and more on food imports. In arid and semiarid regions, crops commonly utilize less than half of the annual rainfall productively, with the remainder lost as runoff, soil evaporation or drainage. For example, transpiration from traditionally farmed maize amounted to just 15% of seasonal rainfall in a semiarid area of Zimbabwe (Butterworth 1997); on the Deccan Plateau of India, 59% of rainfall was lost as runoff or drainage from a traditional cropping system (Ong et al. 1992), and 30–45% of rainfall was lost from millet crops in semiarid Niger by direct evaporation from the soil (Wallace 1991). Furthermore, significant quantities of rainfall may be wasted if it occurs during off-season of crop, for example, in Hyderabad, India, where 20% or 152 mm of rain occurs outside the normal growing season

(Ong et al. 1992). Thus, rainfall is typically utilized very ineffectively by rainfed agriculture in arid and semiarid zones, and there is great scope for enhancing biomass production in these regions by increasing the utilization of water by incorporating perennial vegetation (which can utilize this water for producing biomass) in cropping system.

3 Why Agroforestry for Water-scarce Areas?

Due to increase in population of human and cattle, there is increasing demand of food as well as fodder, particularly in developing countries like India. Each year, farmers of the world would have to feed 81 million more people irrespective of change in weather. There is little scope to increase food production by increasing the area under cultivation. Hence, there is a need to devise such production systems which can produce food from marginal agricultural land and are also capable of maintaining and improving quality of soil and environment. This can be achieved through agroforestry. Agroforestry is a dynamic, ecologically based, natural resource management system that, through the integration of trees in farm and rangeland, diversifies and sustains smallholder production for increased social, economic and environmental benefits (Leakey 1996). It makes use of the complimentarily relationship between trees and crops, so that the available resources can effectively be utilized. It is a practice that supports the environment and has an obvious landscape benefit. Efficient and modern versions of agroforestry have been developed that are adapted to the constraints imposed by mechanization. The efficient agroforestry systems remain productive for the farmer and generate continuous revenue, which is not feasible in arable land. Agroforestry allows for the diversification of farm activities and makes better use of environmental resources.

In India, the current area under agroforestry is estimated as 25.32 million hectares (m ha) or 8.2% of the total geographical area (TGA) of the country. There is further scope of increasing the area under agroforestry in the future by another 28.0 m ha (Dhyani et al. 2013). The major share of the land to be brought under agroforestry will come from fallows, cultivable fallows, rehabilitation of degraded pastures and management of problem soils. Thus, a total of 53.32 m ha, representing about 17.5% of the total reported geographical area (TRGA) of the country, could potentially be brought under agroforestry in the near future, which will make agroforestry a major land use activity, after agriculture (140.86 m ha, 46.08% of the TRGA) and forestry (69.63 m ha, 22.78% of the TRGA) in India (Dhyani et al. 2013). At present agroforestry meets almost half of the demand of fuel wood, 2/3 of the small timber, 70–80% wood for plywood, 60% raw material for paper pulp and 9–11% of the green fodder requirement of livestock, besides meeting the subsistence needs of households for food, fruit, fibre, medicine, timber, etc. However, current biomass productivity per unit area and time is less than 2 Mg $ha^{-1}year^{-1}$. Agroforestry practices have demonstrated that this could be safely enhanced to 10 Mg $ha^{-1}year^{-1}$ by carefully selecting tree-crop combinations (Mathukia et al. 2016).

3.1 Improving Water Productivity (WP)

In a crop production system, water productivity (WP) is expressed as crop production per unit volume of water and can be expressed as kg m^{-3}. The water productivity term plays a crucial role in modern agriculture which aims to increase production per unit of water used, both under rainfed and irrigated conditions. This can be achieved through:

1. Increasing the marketable yield of the crops for each unit of water transpired
2. Reducing the outflows/losses
3. Enhancing the effective use of rainfall, of the water stored in the soil, and of the marginal quality water

The first option refers to the need for improving crop yield; the second one intends to increase the beneficial use (water uptake-transpiration) of water supply against the non-beneficial losses (evaporation); the third aims to utilize the water resources efficiently. All these options lead to the improvement of the on-farm management aspects of crop growth, through the application of the best crop management practices which will permit to use less water for irrigation, decrease evaporation losses, optimize fertilizer supply, allow better pest control, minimize energy consumption and improve soil conditions. This is more important in arid and semiarid regions, where the farmers are frequently constrained to apply deficit irrigation strategies and to manage water supply in accordance with the sensitivity of crop's growing stages to water-stress. Below is a list of the situations in which agroforestry can increase water productivity:

1. Understorey vegetation comprises C3 plants, e.g. cotton and C3 grasses, which shows better water productivity as compared to C_4 species.
2. Tree shade increases humidity of understorey vegetation in semiarid climates, e.g. parkland systems and windbreaks.
3. Planting of trees as contour hedgerows on hill slopes increases infiltration and reduces runoff.
4. Presence of deep water beyond the reach of crop rooting systems.
5. Trees can use rains that fall outside the cropping season.
6. Trees have canopy architecture that intercepts high amounts of water per unit shade.

3.2 Better Resource Capture

Agroforestry has attracted considerable interest because of its potential to maintain or enhance agricultural productivity in areas where high-energy input and large-scale agriculture are impractical. Cannell et al. (1996) proposed that agroforestry may increase productivity if the trees capture resources that are underutilized by annual crops. Agroforestry offers substantial scope to improve system productivity by increasing exploitation of available light, water and nutrients. To achieve this, the trees and crops must capture a greater proportion of the available resources than equivalent sole stands and/or use these more efficiently to produce dry matter. It is vital that the trees exhibit complementarities with associated crops rather than being competitive. Complementarities may be either spatial or temporal; the former occurs when trees and crops exploit different resource pools, for example, when deep-rooted trees use water and nutrients, which shallow-rooted crops cannot access. Temporal complementarities occur when trees and crops make their main demands on available resources at different times, for example, when trees are deciduous during at least part of the cropping season or continue to extract water during the dry season (Ong et al. 1996). Significant complementarities of water use may occur naturally if trees with suitable leafing phenology or rooting architecture are used.

There is substantial experimental evidence to support the hypothesis that agroforestry may increase productivity by making better use of available resources. Ong et al. (1992) reported that hedgerow plantings of sole *Leucaena leucocephala* extracted more of the available soil water than sole crops or intercrops of sorghum and pigeon pea at Hyderabad, India. Widely spaced alley crops (4.4 m between hedges) extracted more water than sole *Leucaena*, indicating that the agroforestry system was most effective in exploiting available water. Similarly, Ong et al. (1996) observed substantial improvements in productivity resulting from increased utilization of annual rainfall from 40% to 80% in agroforestry systems containing perennial pigeon pea (*Cajanus cajan*) and groundnut (*Arachis hypogaea*). Almost half of the annual water use (416 mm versus 887 mm) occurred between January and June, when only 211 mm of rainfall, indicating that 205 mm was extracted from soil reserves. Droppelmann et al. (2000) and Ong et al. (2000) reported that the yield of intercrop (sorghum) in combinations with pruned trees was similar to their yields when grown as monocrops. This shows that there can be complementarities in resource use between different agroforestry system components.

3.3 Efficient Use of Nutrients

Trees can act as a safety net by capturing nutrients leached from the topsoil, and they can return these to the soil surface as litter (Rowe et al. 1998). There is a general pattern of higher fertility under tree crowns that is usually characterized by a gradual decline with increasing distance from the trunk and increasing soil depth and appears to respond to several factors including land form, soil type, tree density, tree size/age and management practices, as well as tree species (Bayala et al. 2015). Danso et al. (1992) reported rates of N accumulation of 43–581 kg N ha^{-1} $year^{-1}$ by several tropical plantation trees, even though not all N originated directly from the atmosphere. However, several important tree species, including some *Acacia* spp, have been shown to accumulate N at very low rates (<50 kg N ha^{-1} $year^{-1}$). By the same mechanism, N-fixing tree species, such as *Senna* spp., increase nutrient availability to crops (Duarte et al. 2013).

Trees can access nutrients from subsoil that are not accessible to shallower-rooted plants, including nutrients leached through surface soil (Rowe et al. 1998). These nutrients can subsequently become available to annual plants through above- and below-ground litter production. This nutritional benefit to crops is delivered slowly, depending on the speed of litter decomposition and nutrient supply. The release of nutrients was species specific. In a agri-horti systems, Soni et al. (2013a) reported faster release of nitrogen in *Citrus aurantifolia* and *Aegle marmelos*. The N release by the litters of *Cordia myxa* was very slow. The slowest nitrogen release in *C. myxa* could be ascribed to its slow decomposition due to higher lignin content (45.8%) as compared to *C. aurantifolia* (19.8%) and *A. marmelos* (15.3%). Trees can also trap dust and sediment and be the sites for nutrient accumulation from animals (including birds) that perch on them or seek shelter in their shade, where they urinate or defecate (Mills et al. 2012).

3.4 Optimize Water Capture

The greatest challenge for agroforestry in water-scarce areas is to identify species combinations and management systems which optimize the capture of scarce available water supplies and minimize the inevitable competition between trees and crops (Ong et al. 2015). One of the principal biophysical premises of agroforestry in dryland systems is to conserve and maximize the use of limited water supplies (Broadhead et al. 2003a, b; Ong et al. 2006). Competition for water between crops and trees in agroforestry systems is another challenge encountered in arid and semiarid regions. However, this competition varies in all three spatial dimensions, as well as with time, depending on tree phenology and age (Teixera et al. 2003). Many tree root systems can access water from deeper soil horizons than herbaceous or annual plants. A review by Van Noordwijk et al. (2015) concluded that generalization of tree root architecture was not possible because of the variety of tree root system geometries that exist without clear relationships between width and depth of root systems and those of crowns. Other data from Australia, North America and Africa show a common basic geometry of root systems of tall single-stemmed trees, resulting in a root influence zone that extends out to approximately 3–3.5 times the tree height. Competitive pressure from trees is especially high close to the trees (1.5–2 tree heights), where high root density enables high rates of soil moisture extraction (Huth et al. 2010). In water-scarce slopping lands, agroforestry may improve water-use-efficiency by reducing the unproductive components of the water balance, such as runoff, soil evaporation and drainage (Bayala et al. 2015). Approximately 40% of the rainfall received by a watershed in Niger was lost to soil evaporation and 33–40% to drainage, with the smallest proportion of 6–16% being used for transpiration by pearl millet (Rockstrom 1997). Such studies indicate that high proportions of potentially available water, which are lost to biological production, might be captured by incorporating trees into land use systems, although effects on groundwater recharge may also need to be considered (Ong et al. 2006).

In addition, many trees in agroforestry systems capture water resources that would not be put to productive use in the absence of trees, mainly from deep soil layers beyond the reach of annual crops.

3.5 Light Capture

Competition for light is another important consideration between trees and crops in agroforestry systems. Trees reduce the amount of sunlight reaching soils and crops through shading. Light capture is influenced by both environmental and plant factors such as tree leaf area, leafing phenology, crown structure and crown management. Unless trees are leafless during the cropping season or heavily pruned, competition can be substantial. Under *Faidherbia albida*, which sometimes exhibits 'reverse phenology' by shedding leaves at the beginning of the rainy season and foliating in the dry season, light interception is generally considered to be low and not to affect crop production significantly (Boffa 1999). Light competition, of course, is of little importance in rotational or segregated agroforestry systems, where trees and crops do not occur in the same space at the same time. Competition for light has been comprehensively studied in a wide range of tropical and temperate agroforestry systems and general models developed at various levels of spatial and temporal disaggregation (Charbonnier et al. 2013).

4 Factors Responsible for Increasing Productivity in Agroforestry

Agroforestry offers promising option for efficient and sustainable use of land and water. Where water is more limiting than land, it is better to maximize yield per unit of water and not yield per unit of land. Agroforestry has the potential to improve water productivity in two ways as the presence of trees may increase the quantity of water used for tree or crop transpiration and may also improve the productivity of the water that is transpired by increasing the biomass of trees and crops produced per unit of water used. Below is a list of the factors which can increase the water productivity in agroforestry in water-stressed ecologies:

4.1 In-situ Soil Organic Matter Enrichment

Agroforestry systems are assumed to be superior to other cropping systems with respect to organic matter addition. In arid region of Bikaner, Soni et al. (2008) reported significantly higher soil organic carbon (SOC) in agroforestry systems

(AFS) as compared to traditional cropping system (TCS). Significantly higher SOC was recorded in upper soil layers of 0–5 cm and 5–10 cm. The increase in SOC was recorded from 0.09% in TCS to a maximum of 0.39% in agroforestry systems with *Acacia tortilis*, and it was in the order *Acacia tortilis* > *Acacia senegal* > *Colophospermum mopane* > *Prosopis juliflora* > *Dichrostachys nutan*. Woody nitrogen-fixing plants can substantially improve the balance and availability of N in agroecosystems. Within agroforestry systems, understanding the temporal impact of trees on soil nutrients is critical for determining the net benefit to crops. Crops respond to available forms of nutrients that fluctuate over the course of a cropping season. The synchronization of seasonally varying soil nutrient supply with plant demand is required for a tree to have a positive impact on crop production (Palm 1995). Comparing relative yields of understorey grass planted in mesquite (*P. juliflora*) and non-mesquite soil, Tiedemann and Klemmedson (1973) found that plants grown in non-mesquite soil were more limited by N, P, K or S availability than those grown in mesquite soil. By experimentally maintaining optimal soil water levels, they concluded that higher grass biomass production in mesquite soil was due to soil nutrient status rather than water relations.

4.2 Reduction in Excessive Transpiration

In hot windy weather, the rate of loss of water through plants by transpiration can be very high and can result in early depletion of limited soil moisture reserves. This in turn can lead to serious water-stresses developing in plants, both crops and weeds, before their cycle of growth to maturity has been completed. When crops are exposed to strong winds in a dry environment, the water that has been transpired by the crop is rapidly removed from the leaf surfaces into the atmosphere. This encourages a more rapid movement of water up through the crop and much greater absorption of water from the soil. Strong winds can therefore cause excessive crop transpiration rates and an unnecessary loss of soil water. Windbreaks significantly reduce wind speed and so reduce crop transpiration rates and the unnecessary loss of soil water. Windbreaks are usually established by planting single, double or triple rows of trees, but tall grass species may also be used. Well-designed windbreaks will significantly reduce evapotranspiration rates of crops in windy conditions resulting in the conservation of soil water and less subsequent moisture stress when water is limiting. A 50% reduction in wind velocity (from 32 to 16 km h^{-1}) will reduce evapotranspiration rates by 33% (McCall and Gitlin 1973). Windbreaks may provide additional benefits to crops by reducing mechanical damage and the loss of flowers and by creating better conditions for insect pollination. They are also beneficial in reducing wind erosion, especially in fine sandy and silty soils, and in diminishing air pollution problems.

4.3 Modification in Microclimate

Trees create a unique microenvironment around them (Munn 1991) by positively modifying their underneath soil physicochemical properties and by direct influence on sunlight and atmospheric conditions (Moody and Jones 2000). Transpiration and canopy are the main factors affecting air temperature, wind speed, quantity and quality of light and soil temperature, pH, moisture and nutrient availability (Zemmrich et al. 2010). So, there is the potential for microclimate modification in agroforestry systems, due to the presence of an elevated tree canopy. This may alter not only the radiation but also the humidity and temperature around an understorey crop. Some evidence for this has been found where crops have been grown using trees as shelterbelts, and decreases in mean saturation deficit of the atmosphere have been reported for several crops (Brenner 1996).

The presence of trees modifies the microclimatic conditions in ways that improve the water-use-efficiency of understorey crops (Wallace 1996). Several factors may be involved. Firstly, shading by the trees may increase the fraction of available water used for transpiration by decreasing soil evaporation, particularly when the crop canopy is sparse and rain is received as frequent, low-intensity events. Under these circumstances, any reduction in the quantity of radiation reaching the soil decreases evaporation as this process is primarily energy-limited. Decreased wind speed at ground level may also limit evaporation. Secondly, agroforestry may confer microclimatic benefits by decreasing the air temperature, wind speed and saturation deficit experienced by understorey crops, thereby reducing evaporative demand (Monteith et al. 1991). The potential benefits of shade are therefore likely to depend on tree spacing and age, canopy structure, incident radiation, shading intensity and the photosynthetic pathway of the understorey crop. Thirdly, shading may alter the surface temperature of understorey crops in ways that benefit their phenology and productivity (Monteith et al. 1991; Vandenbelt and Williams 1992). In areas of high incident radiation and ambient temperature, tissue temperatures frequently exceed optimal levels in unshaded crops, particularly during drought periods; under such conditions, partial shade may exert an ameliorative influence by bringing temperatures within the optimum range.

Gain in total biomass production can be achieved when modification of the microclimate by trees increases the water-use-efficiency of the crop (Elfad 1997; Livesley et al. 2004). Trees can increase soil water content underneath their canopies if the water ‘saved’ by reduced soil evaporation and funnelling of intercepted rainfall as stem flow exceeds that removed by the root systems beneath tree canopies (Ong and Leakey 1999).

In arid open woodlands in southern Australia, *Acacia papyrocarpa* trees provide micro-habitats beneath their canopies with modified temperature and light climate. The higher organic matter content of soils beneath *A. papyrocarpa* canopies (Facelli and Brock 2000) improves soil macroporosity and texture, which can affect the infiltration and retention of water (Joffre and Rambal 1988) and root penetration (Pugnaire et al. 1996). These modifications to soils and microclimates have beneficial effects on the growth and survival of some plants occurring in these microhabitats (Prider 2002). Soils beneath *A. papyrocarpa* canopies retain more water during warm, dry periods than inter-canopy soils (Facelli and Brock 2000; Prider 2002). During the warmer months, they provide a moister microenvironment with a lower evaporative demand and protect plants from high radiation loads and high temperatures.

Shade beneath savannah tree canopies influences subcanopy microclimate and biomass production by reducing temperature maxima and evapotranspiration and by increasing relative humidity (Belsky et al. 1993; Amundson et al. 1995). In Kenyan savannahs, soil temperatures declined by 5–12 °C under *Acacia tortilis* (Dancette and Poulain 1969). The lower heat load beneath tree canopies reduces water-stress and increases biomass of below-crown species (Amundson et al. 1995). Increased biomass production in the below-crown zone draws down the higher soil water resulting from reduced evapotranspiration below tree crowns, offsetting any increase relative to open sites (Belsky et al. 1993).

The improved micro-environmental conditions beneath savannah trees favour soil biotic activity, nutrient transformations and improved physical conditions. Coleman et al. (1991) measured higher soil microbial biomass, greater numbers of microbivorous nematodes and larger amounts of mineralizable N beneath savannah tree canopies. Belsky (1994) found higher rates of N mineralization beneath both *Adansonia digitata* and *Acacia tortilis* associated with lower bulk density and higher water infiltration. The tree influence on N availability was greater in more xeric environments. Shading decreased the mean diurnal temperature range and maximum meristem temperature by up to 7 °C relative to monocrop maize in *Grevillea robusta*-based agroforestry systems in semiarid Kenya (Ong et al. 2000). Agroforestry treatments exhibited a potential to optimize the microclimatic conditions for seedling emergence, tillering and ear head emergence at some tree row orientations and distances from the crop in sown wheat in subtropical India (Kohli and Saini 2003). Kohli and Saini (2003) reported that microclimatic conditions under agroforestry were more favourable for wheat growth attributed to reduction in heat load during the post-anthesis period. The deterioration or amelioration of microclimatic conditions in agroforestry with the passage of time should be expected because of altered interaction patterns between sunrays and tree canopy resulting from changing solar elevation and angle of sunrays.

4.4 Increase in Humidity of Understorey Vegetation

The tree crown interacts with solar radiation through absorption and scattering. These processes vary with the leaf structure, size, shape, orientation, distribution and age and density of the leaf layers, as well as crown volume (Monteith 1975). All these critical parameters are different among different tree species and individuals of the same species with different age or size (Rosenberg 1974; Bengtson et al. 2006). Limiting light availability also helps maintain soil moisture (Reed 2007).

The difference between open and shade condition for temperature and relative humidity increased with increase in canopy age and modification in microclimate became more pronounced. These changes in the microclimatic conditions influenced the physiological process in the understorey crops, thus affecting the crop yield (Chauhan et al. 2013).

4.5 Absorption of Water from Deeper Soil Horizon Beyond the Reach of Crop Rooting Zone

Trees also redistribute water through processes known as hydraulic lift and hydraulic redistribution, which involve the transfer of water from relatively wet deeper soil horizons to drier surface layers (Richards and Caldwell 1987). This usually occurs nocturnally when the transpiration rate is low during the day along water potential gradients created by variation in soil salinity (Hao et al. 2010). This process is generally found in species with dimorphic root systems which use water from both shallow and deep soil layers. The main function of deep roots is to absorb water from subsurface soil layers, while shallow roots absorb water and nutrients from the surface horizons. Hydraulic redistribution has been reported in *Acacia tortilis* (Ludwig et al. 2003).

Hydraulic lift constitutes the missing link in the soil water balance in systems containing mixtures of annual crops and woody perennial species. Published estimates of the volume of water lifted range from 5% to 30% of daily evapotranspiration, suggesting that hydraulic redistribution can postpone the development of water-stress and mitigate the impact of soil drying in the surface horizons (Oliveira et al. 2005; Warren et al. 2005). Several studies have shown that hydraulic lift enhances water availability to plants (McMichael and Lascano 2010; Shen et al. 2011) and ecosystems, thereby promoting microbial processes that release nutrients from organic matter and soil minerals (Munoz et al. 2008). Hydraulic redistribution may, therefore, contribute significantly towards the water supplies needed to support grain filling in associated crops in agroforestry systems (Ludwig et al. 2004).

4.6 Utilization of Rains that Fall Outside the Cropping Season

In annual systems where the land lies bare for extended periods, residual water remaining in the soil after harvest and off-season rainfall are often unused, particularly in areas of unimodal rainfall. For instance, at Hyderabad, India (annual rainfall 800 mm), substantial available water remained in the 45–90 cm horizons after harvesting sorghum and pigeon pea (Ong et al. 1992). About 20% of the annual rainfall occurs outside the normal cropping season when it could be used by perennial species. The scope for improving water use is therefore considerable, as a maximum of 40% of the annual rainfall was utilized by the most effective cropping systems and the remainder was lost as runoff (26%) or drainage (33%) (Ong et al. 1992). In drier areas such as Syria and Niger, soil evaporation may account for 30–60% of the annual rainfall (Cooper et al. 1983; Wallace 1991). Thus, any decrease in soil evaporation, runoff or drainage resulting from increased shading, reduced soil temperature, windbreak effect of the trees or increased abstraction of water at depth or during the dry season would increase the proportion of rainfall used for transpiration. Interception losses are lower when the tree canopy is sparse (5–10%) (Wallace et al. 1995). The hypothesis that agroforestry may increase productivity by capturing a larger proportion of the annual rainfall (Ong et al. 1992) was supported by the Hyderabad studies, which demonstrated that improvements in annual rainfall utilization from 40% to 80% were possible in perennial pigeon pea (*Cajanus cajan*)/groundnut agroforestry systems, primarily because the use of off-season rainfall was increased (Marshall 1995).

With their limited growing seasons, annual crops can only use a finite portion of available water supplies. In India, sorghum transpiration accounts for 41% of rainfall (Ong et al. 1992), while in Niger, millet transpiration accounts for 6–16% of the annual rainfall, with the remainder going to evaporation, runoff and drainage (Rockstrom 1997). The trials confirm that intercropping with trees can result in much higher capture of annual rainfall. Particularly successful combinations include pigeon pea/groundnut where transpiration consumed 85% of the annual rainfall (Ong and Black 1994) and agroforestry systems that coupled *Grevillea*/maize, where transpiration reached 70% (Lott et al. 2002). This evidence fits well with the hypothesis that trees increase water productivity in two distinct ways (Rumley and Ong 2012):

1. Increasing the quantity of water used and transpiration (Tw)
2. Increasing biomass per unit of water consumed (ew)

$$\text{Biomass} = (\text{ew}) \times (\text{Tw})$$

4.7 Interception of High Amounts of Water per Unit Shade

There are also considerable differences in the pattern of rainfall reaching the ground in many plant communities, because of the interception by the tree crown. The water may be subsequently transferred to the soil by channelling down the main stem or by dripping from the branches. The stem flow is greatly enhanced by branches and leaves, which are inclined upward. Stem flow produces a great concentration of water around the base of the trunk, which may be significant ecologically (Monteith 1975). Interception of rainfall by trees and the subsequent stem flow induces pattern of soil wetting nearby, for smaller plants (Goodall and Perry 1981). An enhanced concentration of water and nutrients creates favourable microenvironments, which in turn enhance the establishment, growth and persistence of the herbs beneath (Munn 1991). The tree canopies in agroforestry systems intercept the rain

Fig. 15.2 Silvopasture system with *Colophospermum mopane*

and reduce runoff. In a study at CAZRI, it was found that in *Acacia tortilis*-based silviopasture system, canopy interception was 21.4%, whereas in *Colophospermum mopane*-based silvopasture system (Fig. 15.2), it was 13.1% (Roy et al. 2011). Average surface runoff in *A. tortilis*-based silvopasture system was 53% higher than in *C. mopane*-based silvopasture system. This indicated that hydraulic response to rain is dominated by plant species character; however, the per cent annual runoff and soil erosion were very low in situations with trees on agricultural fields in comparison to bare soil condition. Thus, the enhanced use efficiency of rain water by woody species in agroforestry systems improves agricultural productivity.

4.8 Improvement in System Productivity

Agroforestry can provide a wide range of benefits in addition to the effects of trees on crop yields, and in some circumstances the value of these benefits may outweigh the negative impacts on crop yield. A reduction in crop production might be acceptable to a smallholder farmer, if fruits are sold or wood is produced on-farm and substituted for collected or purchased firewood or for animal dung, which can then be used as soil amendment. According to State of Forest Report (SFR 2013), volume of trees under agroforestry is 1124.097 million m^3 (Table 15.1). Saving labour through producing fodder and firewood on farm rather than having to collect it can be a key feature of smallholder system intensification (Van Ginkel et al. 2013). Many farmers also state the provision of shade as one of the primary benefits of trees on their farms, since it reduces heat stress on plants, livestock and people (Muthuri et al. 2014). Among different agroforestry systems, *Acacia*

Table 15.1 Species-wise volume of trees under agroforestry systems in India

S. No.	Species	Volume (m cum)
1	*Acacia nilotica*	29.03
2	*Acacia catechu*	4.57
3	*Acacia lenticularis*	8.36
4	*Albizia* spp.	13.48
5	*Anacardium occidentale*	5.34
6	*Areca catechu*	7.32
7	*Artocarpus heterophyllus*	21.85
8	*Azadirachta indica*	75.98
9	*Bombax ceiba*	10.00
10	*Borassus flabelliformis*	64.12
11	*Butea monosperma*	28.49
12	*Cocos nucifera*	60.08
13	*Dalbergia sissoo*	18.01
14	*Eucalyptus* sp.	21.50
15	*Ficus benghalensis*	14.17
16	*Ficus racemosa*	7.95
17	*Ficus* sp.	8.56
18	*Gmelina arborea*	5.31
19	*Grevillea robusta*	7.52
20	*Grewia optiva*	5.20
21	*Holoptelea integrifolia*	4.71
22	*Hevea brasiliensis*	9.06
23	*Madhuca longifolia*	63.94
24	*Mangifera indica*	149.35
25	*Phoenix sylvestris*	10.32
26	*Pinus kesiya*	7.14
27	*Pinus roxburghii*	34.40
28	*Populus* ssp.	7.49
29	*Prosopis cineraria*	9.58
30	*Quercus incana*	5.22
31	*Shorea robusta*	21.52
32	*Syzygium cumini*	18.75
33	*Tamarindus indica*	13.24
34	*Tectona grandis*	11.27
35	*Terminalia arjuna*	5.99
36	*Terminalia bellerica*	5.23
37	*Terminalia crenulata*	5.41
38	*Toona ciliata*	5.31
39	*Ziziphus mauritiana*	8.44
40	Rest of species	303.32
Total		1124.097

Source: SFR (2013)

Table 15.2 Improvement in system productivity and resource utilization by agroforestry systems

Agroforestry system	Crop benefits and resource utilization	References
Mustard with *Hardwickia binata*	30% higher crop yield in tree-integrated system	Shanker et al. (2005)
Maize with red alder (*Alnus rubra*)	32–58% of the total nitrogen in alley-cropped maize came from nitrogen fixed by the tree species	Jose et al. (2004)
Crop with hybrid poplar and silver maple (*Acer saccharinum*)	Double nitrate content in soil near trees due to litter fall available to crop, through fall and stem flow contributed 10.99 and 15.22 kg N ha^{-1} $year^{-1}$	Smith (2010)
Green gram with *mopane*	Tree-integrated plots had 2–36% less soil water, increased soil organic matter and decreased available PO_4-P, NH_4-N and NO_3-N with similar crop biomass and system productivity indicating better resource utilization	Singh and Rathod (2007)
Peanut with *Choerospondias axillaris*	Peanut mainly uses N in the surface soil (10–15 cm), but the trees can use N in deeper soil (>40 cm) which increased system N use efficiency compared with the peanut monocropping system	Zhang et al. (2008)

auriculiformis + sweet orange (*Citrus sinensis*) + bottle gourd-based agri-horti-silvi system gave maximum total outturn (₹71,028 ha^{-1} $year^{-1}$) closely followed by *A. auriculiformis* + guava + bottle gourd system (₹69,286 ha^{-1} $year^{-1}$) in dry regions of West Bengal. This agri-horti-silvi system will be of multifarious utility to the farmers because it not only provides fuel wood, timber, fruits and crop produce but also helps to enrich the soil health (Banerjee and Dhara 2011). Agroforestry systems utilize the resources efficiently and increase the overall system productivity as compared to monocropping (Table 15.2).

5 Agroforestry Management Practices for Effective Use of Available Water

Introducing trees into cropped fields results in changes in the soil water balance. Trees which retain foliage in the dry season can make use of residual water stored in the soil profile and any rainfall received after the crop harvest. On an annual basis, therefore, trees can increase the productive use of water. Trees can also increase water utilization during the growing season. If they are more deeply rooted than crops, and seasonal rainfall is sufficient to cause infiltration beyond the crop rooting zone, trees can utilize water that would otherwise have been lost as drainage (Van Noordwijk 1996). Shading by the tree canopy reduces evaporation from soil (Jackson and Wallace 1999) and may thereby enhance the availability of water to crops during the growing season. Similarly, when planted along contours, woody hedges promote infiltration of water into the soil and thus reduce runoff from sloping fields (Kiepe 1995), making more water available for crop growth. Further benefits of agroforestry can result from modifications to microclimate by trees which increase the water-use-efficiency of crops (Wallace 1996). Some of these advantages of growing crops with trees can, however, be negated by evaporation of intercepted rainfall from the tree canopy (Wallace 1996; Jackson 1998). These include reductions in soil evaporation resulting from shading by the tree canopy and reduced air movement through the understorey environment, microclimatic modifications arising from reductions in air temperature, wind speed and saturation deficit which decrease crop water use and decreases in tissue temperature which benefit the phenology and productivity of understorey crops by minimizing heat stress (Cannell et al. 1996). The key question is whether these potential benefits are outweighed by the detrimental effects of competition for available resources between trees and crops.

If trees deprive the crop of shared resources in limited supply, crop production in agroforestry will be impaired (Anderson and Sinclair 1993) and the food security of the farmer threatened. It is, therefore, critical for the success of agroforestry that competition for resources between trees and crops is avoided or at least minimized. Hence, a major challenge for management of agroforestry is to control competition and encourage 'complementarity' between trees and crops in resource use. Complementarity occurs when components of mixed vegetation utilize spatially or temporally distinct sources of resources and consequently avoid competition (Anderson and Sinclair 1993). A key to the successful design and implementation of agroforestry in arid and semiarid regions understands the sources of water used by the tree and crop components of the system. This enables evaluation of the extent of competition and complementarity in water use, which dictates the management strategies most appropriate for specific sites.

5.1 Selection of Tree Species

Correct selection of trees is of prime significance in water-stressed region for the development of agroforestry (Tables 15.3 and 15.4). In the agroforestry systems with limited water supply, the selection of appropriate plant species based on their water use should be considered to optimize vegetation suitability, survival and stability. In addition, sustainable use of water resources should also be considered. Successful incorporation of trees on crop fields in water-stressed areas requires identification of species, which use limited water supplies efficiently, impose minimal competition on associated crops and meet farmers' needs. Some tree species with consistently limited competitive or beneficial effects on associated crops have been identified (ICRAF 1997).

Beniwal et al. (2008) studied soil moisture depletion in agri-silvi-horti systems comprising different tree species and observed that soil moisture depletion from the profile was maximum in *C. mopane* followed by *D. sissoo* and *C. aurantifolia*. The extensive root system of *C. mopane* resulted in higher soil moisture extraction from cropping zone as compared to *C. aurantifolia* and *D. sissoo* (Table 15.5). They further reported that the root biomass density of *C. mopane* at a radial distance of 1.0–2.5 m

Table 15.3 Tree/shrub/grass species suitable for agroforestry in different parts of arid regions

S. No.	Nature of land	Trees/shrubs/grasses
1.	Sandy soils	**Trees/shrubs:** *Acacia tortilis, Prosopis cineraria, Albizia lebbeck, Azadirachta indica, Leucaena leucocephala* **Grass species:** *Lasiurus sindicus, Cenchrus ciliaris, Cenchrus setigerus*
2.	Shallow soils	**Trees/shrubs:** *Acacia tortilis, Prosopis juliflora, Dichrostachys glomerata, Ailanthus excelsa, Ziziphus mauritiana* **Grass species:** *Cenchrus ciliaris, Dichanthium annulatum, Panicum antidotale*
3.	Sandstone rocky sites	**Trees/shrubs:** *Albizia lebbeck, Boswellia serrata, Acacia senegal, Cassia auriculata* **Grasses:** *Cenchrus ciliaris* and *Cenchrus setigerus*
4.	Saline areas	**Trees/shrubs:** *Tamarix auriculata, Prosopis juliflora , Prosopis tamarugo, Salvadora oleoides,* species of *Atriplex, Kochia, Haloxylon* and *Balanites* **Grass species:** Species of *Sporobolus, Panicum, Aeluropus, Dichanthium* and *Chloris*
5.	Shifting sand dunes	**Trees/shrubs:** *Prosopis juliflora, Prosopis cineraria, Acacia senegal , A. tortilis, Albizia lebbeck, Tamarix articulata, Calligonum polygonoides* **Grasses:** *Cenchrus ciliaris, Saccharum munja*
6.	Horticultural fruit trees for arid areas	**Trees/shrubs:** *Ziziphus mauritiana, Punica granatum, Psidium guajava, Phoenix dactylifera, Aegle marmelos, Annona squamosa*

Source: Chundawat and Gautam (2010)

Table 15.4 Tree/shrub/grass species suitable for agroforestry in other water-stressed areas (other than arid region)

S. No.	Components	Trees/shrubs/grasses
1.	Tree components	*Acacia nilotica, Ailanthus excelsa, Leucaena leucocephala, Azadirachta indica, Madhuca latifolia, Eucalyptus, Melia dubia, Anthocephalus cadamba, Gliricidia sepium*
2.	Horticultural components	*Psidium guajava, Tamarindus indica, Citrus* spp. *Annona squamosa, Emblica officinalis, Ziziphus* spp., *Mangifera indica, Punica granatum*
3.	Grasses/shrubs	Species of *Panicum*, *Cenchrus, Cassia*

Source: Chundawat and Gautam (2010)

Table 15.5 Profile soil moisture (up to 60 cm soil depth) under different tree species after a rainfall of 67 mm

Species	Lateral distance (meter)	Dates		
		19.09.05 (3 DAR)	23.09.05 (7 DAR)	3.10.05 (17 DAR[a])
Citrus aurantifolia	1.00	40.36	20.86	11.58
Colophospermum mopane		28.59	17.68	12.63
Dalbergia sissoo		32.85	25.56	16.54
C. aurantifolia	2.50	41.08	29.32	24.95
C. mopane		35.10	22.61	11.87
D. sissoo		39.26	29.68	19.39

Source: Beniwal et al. (2008)

[a] DAR depicts days after rainfall

was more as compared to *D. sissoo* and *C. aurantifolia*. The fibrous and thin roots of *C. mopane* were 2.4 and 16.3 times more than *C. aurantifolia*, which compete with intercrops for moisture. Since root biomass and soil moisture extraction by *C. aurantifolia* in cropping zone (i.e. 2.5 m radial distance) was less, it can perform well in agri-horti system with minimum effect on crop growth and yield.

A key factor determining species choice is leafing phenology, as this influences the pattern and rate of soil water abstraction, and hence the extent of effects on associated crops (Broadhead et al. 2003a, b; Eamus and Prichard 1998). Elucidation of the leafing patterns of trees relative to the prevailing climatic conditions and growth periods of associated crops is essential for a full understanding of the functional aspects of agroforestry systems. Seasonal variation in rainfall and consequent effects on soil moisture availability are predominant in determining tree water status (Reich and Borchert 1984), although the structural and functional state of the trees is also important (Reich 1995) as periods of maximum leaf cover do not always coincide with the rainy seasons. Indeed, a small number of ‘hygrophobic’ species shed their leaves during the wet season and flush again prior to or at the onset of the ensuing dry season (Koriba 1958). Temporal complementarity between trees and crops minimizes competition for water and increases the utilization of off-season rainfall which would be lost in annual cropping systems. As off-season rainfall frequently comprises 15–20% of total annual rainfall in the semiarid tropics, this represents a substantial supply of water which cannot be used by annual crops but could be used by trees, thereby increasing overall system productivity (Ong et al. 1992; Lott et al. 2000a, b). An example of temporal complementarity, where trees and crops make their main demands on available resources at different times, involves *Faidherbia albida*; this species enhances crop production because its reverse phenology causes leaves to be shed at the beginning of the rainy season, so supplying nutrients to the soil, while leaf flushing (production of new leaves) occurs at the start of the dry season when annual crops are approaching maturity (Sanchez 1995). Leaf shedding during periods of low soil moisture content provides an important tool for reducing the transpiring area and hence the depletion of residual soil moisture (Ludlow and Muchow 1990; Sinclair 2000). This emphasizes the potential benefit of adopting trees, which shed their leaves at appropriate times of year, as these are likely to be much less competitive with crops than species, which maintain a full canopy throughout the year in water-limited environments.

Water-use-efficiency of different tree species should be considered while selecting trees in agroforestry systems. Under water-stress conditions, plants tend to minimize transpiration by closing stomata to conserve and prevent excessive loss of water and lowering stomatal conductance, thereby resulting in lower photosynthesis (Zamora et al. 2006). The moderate water-stress enhanced the water-use-efficiency of *Hippophae rhamnoides* and *Caragana intermedia* through decreasing their photosynthesis and transpiration rates concurrently. Both species have shown a great potential for high water-use-efficiency and improving the soil fertility status in agroforestry systems (Guo et al. 2010).

Gregory (1996) has shown that *Prosopis juliflora* did not much reduce the soil water content in the crop rooting zone and consequently showed less competition with sorghum as compared with *Acacia nilotica* in an agroforestry system. The two leguminous tree species, therefore, showed different types of root morphology and density distribution with depth. Such effects have important implications for modelling of tree-crop competition and interaction. The following characters of tree species are desired in water-stressed ecologies:

1. The trees should have drought tolerance mechanism which includes:
    (a) Deep root system to draw water from deeper soil profile
    (b) Leaf shading in summer to conserve moisture
    (c) Water-binding mechanism
    (d) Other xerophytic characteristics like wax coating hairiness and sunken and covered stomata on leaves to minimize the loss of water through transpiration
2. Tree crops in arid region should have tolerance to soil salinity, saline water and alkalinity, which are common features of arid region.

5.2 System Design to Maximize Productivity

Interactions between woody and crop components in agroforestry can be positive, negative or neutral, affecting the productivity of the system. The aim of agroforestry system designs should be to optimize utilization of available resources. This requires careful examination of the potential interactions between the different system components. Ideal tree species for agroforestry systems should maximize niche differentiation between the tree and crop; deep roots to access nutrients and water are unavailable to the crop and do not hamper crop growth by light interception. The system's spatial design will also influence productivity by determining the zone of interactions between the trees and crops and, therefore, the relative potential benefits. The interactions between components may be manipulated for more benefits through practices like pruning of tree component (above and below ground) and weed control.

5.3 Tree Density

In agroforestry system, mutual interference between trees (both above and below the soil surface) will decrease with deceasing tree density, and the magnitude of the parameters controlling transpiration will be modified. More specifically, as tree density decreases, there is likely to be less competition for water by root overlap between trees, mutual shading will be reduced, and canopy boundary layer conductance will be increased. In an agroforestry system, tree density will also affect transpiration of the associated crop or pasture species by modifying microclimate, and trees may also compete with the associated species for water, both by canopy interception of rainfall and by root uptake of soil water. Modification of the environment by varying tree density is, therefore, likely to have a complex effect on biomass production and water-use-efficiency of components of agroforestry systems, through effects on both photosynthesis and water use. Water use of trees and pasture was studied at three tree densities in an agroforestry experiment where trees were planted at densities of 2150, 304 and 82 stems per ha in a Nelder design. The result showed greatest pasture production at the intermediate tree density, and this was associated with higher water-use-efficiency than was found from pasture under other high and low tree densities (Eastham et al. 1990). Water-use-efficiency was found to be highest in the densely planted trees where mean values for 2 years were 4.6 and 3.9 kg m^{-3}, respectively (Cameron and Rance 1990). Intercropping and high tree density increased water-use-efficiency in runoff agroforestry system in arid region of the Netherlands. The effects of two different tree planting densities (2500 and 833 trees ha^{-1}) of *Acacia saligna* were studied. The improved gross water-use-efficiency (GWUE) of trees at high density was most probably related to lower evaporation losses from the bare soil due to the larger and denser canopy of trees when compared to the canopies of trees at low density (Droppelmann et al. 2000).

5.4 Root or Shoot Pruning

Management practices such as root or shoot pruning prior to the cropping season may be used to modify the temporal patterns of resource capture by trees and minimize competition when supplies are limited (Van Noordwijk et al. 2004). Pruning the tree canopy prior to the cropping season may allow annual crops to exploit available water in the surface horizons by reducing demand by the trees; the trees may also be able to exploit deep water reserves as their canopy regrows during the latter stages of the cropping season (Droppelmann et al. 2000). It is, therefore, essential to consider the implications of increased water use in agroforestry systems for medium- and long-term water budgets. Specific attention should be paid to the source of water used by trees, the rate of depletion below the crop rooting zone and the prospects for deep recharge during periods of high rainfall (Smith et al. 1997). It is particularly important to choose trees with appropriate rooting architecture or leafing phenology to ensure spatial complementarity and avoid major crop yield losses.

Singh et al. (1989) demonstrated that root barriers to 50 cm depth are extremely effective in reducing competition between 4-year-old *Leucaena leucocephala* hedgerows and associated crops in semiarid India. However, the beneficial effects lasted only one season because tree roots reinvaded the crop rooting zone from beneath the root barriers. In contrast, studies in Bangladesh (Hocking 1998; Hocking and Islam 1998) revealed that below-ground competition from a wide range of tree species (mainly fruit trees) was virtually eliminated by pruning the lateral roots off the trees. Likewise, studies in Uganda showed that competition by *Maesopsis emini*, the fastest growing of 12 tree species compared, was completely eliminated by root pruning (Ong et al. 2002). Results with all species showed that overall tree transpiration was not reduced after root pruning because roots that were located deeper increased their rates of sap flow to satisfy transpiration demand from the atmosphere. More importantly, root pruning dramatically improved crop growth.

Different tree canopy management practices, viz. 0, 25, 50 and 75% crown removal, were tried in *Morus alba*-based agroforestry system. It was concluded that 75% crown removal causing less negative effects on crop growth and yield may be adopted as a compromised canopy management practice (Thakur and Singh 2008). According to Kohli and Saini (2003), tree canopy pruning as a management tool can be advocated to provide a favourable microclimate to the intercropped wheat in Northern India. Other studies have shown that regular shoot and root pruning of trees in alley cropping systems may encourage proliferation of fine roots in the surface soil horizons, decreasing spatial niche separation between tree and crop roots and hence the potential for complementarities in the use of below-ground resources (Cannell et al. 1996; Ong and Leakey 1999). Highest water consumptions were found for unpruned trees at high density. Tree pruning decreased water uptake compared to unpruned trees, but soil moisture depletion pattern showed complementarities in water uptake between pruned trees and annual intercrops. The highest values of water-use-efficiency for an individual treatment were achieved when the pruned trees at high density were intercropped with sorghum (1.59 kg m^{-3}) and cowpea (1.21 kg m^{-3}) (Droppelmann et al. 2000).

5.5 Selection of Understorey Vegetation: C_3 Crops

For a given crop variety and climate, there is a well-established linear relationship between plant biomass and transpiration (Steduto et al. 2007). Different kinds of plants are more water efficient in terms of the ratio between biomass and transpiration. C_3 crops, such as wheat and barley, are less water efficient than C_4 crops, such as maize and sugarcane. The most water-efficient crops are the CAM (crassulacean acid metabolism) crops such as cactus and pineapple (xerophytes). Improvement in WP is most likely if the understorey crop is a C_3 species, which is usually light saturated in the open, so partial shade may have little effect on its assimilation. However, the shade will reduce transpiration, with the result that WP increases. Evidence from both semiarid India and subhumid Kenya indicates that WP is about 10% higher in agroforestry systems with a C_3 understorey compared with those with a C_4 understorey (Ong et al. 1996). This may explain why cotton yield in the Sahel is not reduced by the heavy shading of karite (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) in parklands, while yields of millet and sorghum are reduced by 60% under the same trees (Kater et al. 1992). The same process may explain the observation that in the South and Central American savannahs, C_3 grasses are found only under trees and never grow in open grasslands dominated by C_4 grasses. In C_3 crops, in which photosynthesis becomes light saturated at relatively low irradiances, the reduced flux of photosynthetically active radiation (PAR) resulting from partial shading may have little effect on assimilation (Stirling et al. 1990), although this is less likely to apply to C_4 species with their much higher light-saturated photosynthetic rates.

5.6 Use of Saline Aquifers of Dry Regions to Develop Agroforestry Systems

The adaptability of irrigation with saline water is decided by (1) crop salt tolerance limit, (2) nature of soil, (3) quality of saline water, (4) intensity of rainfall, (5) leaching characteristics, (6) availability of fresh water, (7) method for application of irrigation water, (8) climate of the area, (9) soil-water-crop-environment and human resource management practices and finally (10) the saline water irrigation economics. In India, the groundwater surveys indicate that 25–84% of the total groundwater development in the country is poor in quality that is being utilized for irrigation, especially in Rajasthan, Gujarat, Haryana and Punjab (GoI 1998). In past three decades, technologies have been developed to use saline water for the establishment of agroforestry systems in dry regions. Some viable technologies have been suggested to sustain the use of saline groundwater for irrigation in arable crops, forage grasses and medicinal and aromatic plants and even for establishing the forest and fruit trees (Minhas 1996; Bouwer 2002; Tomar et al. 2003a, b, 2010; Qadar et al. 2007, 2008; Dagar et al. 2008, 2012, 2013, 2016; Dagar and Minhas 2016a, b). The traditional approach of sustainable use of saline water has been to increase the frequency of irrigation, which leaches down the salts below the shallower rhizosphere of arable crops (Ayers and Westcot 1985; Dagar et al. 2008). However, enhanced frequency of saline water irrigation may rather aggravate the problem in deep-rooted woody vegetation, because of the additional salt loads going into the soil that likely to persist within the root zone, and may subsequently hinder the plant growth. Nevertheless, such practice demands additional quantities of saline water and thereby results in enhancement of overall salt loads in the soils. Developing low water-requiring fruit-based agroforestry systems for the dry regions and having saline groundwater as the only source of irrigation could be ecologically sustainable and help in improving the socio-economic conditions of the people. Experiment conducted at Bir reserve forest of Hisar showed that fruit-based agroforestry systems improved livelihood of the people, where saline groundwater was the only source of irrigation. Saline water up to 10 dS m^{-1} can be used for growing agri-horti system of *Carissa carandas* with barley (*Hordeum vulgare*) (Fig. 15.3) and *Pennisetum typhoides* as intercrops (Dagar et al. 2016). Fruit trees such as goose berry (*Emblica officinalis*), bael (*Aegle marmelos*), ber (*Ziziphus mauritiana*) and Kaith (*Feronia limonia*) can successfully be established with saline water up to Ec 10 dS m^{-1}. Besides above crops, cluster bean, castor (*Ricinus communis*), mustard (var CR 55, 56), taramira (*Eruca sativa*) and several medicinal crops such as psyllium (*Plantago ovata*), lemon grass (*Cymbopogon fluxuosus*), *Lepidium sativum,Withania somnifera,Adhatoda vasica,Catharanthus roseus* and *Aloe vera* can successfully be grown in isolation as well as agroforestry crops (Dagar and Minhas 2016a). Dagar et al. (2012) found that medicinal and petro-crop*Euphorbia antisyphilitica* produced huge biomass with two to three saline irrigations. Tomar et al. (2003a) evaluated many fodder grasses suitable for dry regions and cultivated using saline water of 8 dS m^{-1} even during summer, when there is scarcity of fodder.

Fig. 15.3 Agri-horti system of karonda (*Carissa carandas*) with barley (*Hordeum vulgare*) irrigated with saline water (Photo by Dr. JC Dagar)

6 Water-use-efficiency of Different Agroforestry Systems

Wallace (1996) proposed that combining trees and annuals directly improves water use in semiarid regions mainly because of a higher efficiency in rainfall utilization by reduced evaporation losses from the bare soil. Better knowledge of water use strategies and drought tolerance of native trees and shrubs is essential for better agroforestry development in arid and semiarid environments. Various land uses, including sole plantations of *Leucaena* and *Eucalyptus*, maize-wheat, *Chrysopogon* grass or turmeric and their tree-crop mixtures were compared for period of 9 years in two sequences for runoff, water use and water-use-efficiency on nine large erosion plots on 4% slope at western Himalayan valley region of India. Sole plantations of *Leucaena* and *Eucalyptus* showed negligible runoff losses and their water use approximated annual rainfall. Agroforestry land uses also reduced runoff and increased water use and water-use-efficiency. Seasonal crops exploited 1.5 m depth of profile more exhaustively than trees. Research indicates that in tree-crop mixtures, more efficient soil water use was observed as compared to monocropping systems (Pratap Narain et al. 1998). A study was conducted at Haryana to find the water-use-efficiency of different tree species planted under micro-sprinkler irrigation. Among four tree species, *Dalbergia sissoo* showed maximum water-use-efficiency in agri-horti-silvi system in all three irrigation levels (100%, 70% and 40%) (Table 15.6).

Table 15.6 Water-use-efficiency (g l^{-1}) of different tree species under micro-sprinkler irrigation system in agroforestry system

Tree species	Irrigation level		
	100%	70%	40%
Dalbergia sissoo	5.36	8.69	10.65
Emblica officinalis	1.69	1.52	2.25
Psidium guajava	1.04	1.23	1.50
Prosopis cineraria	1.28	1.51	0.97

Source: Kaushik et al. (2006)

7 Suitable Agroforestry System for Water-stressed Areas

In most of the arid region of the north-western India, Khejri (*Prosopis cineraria*)-based agri-silviculture system is prominent. Almost in all the fields most useful Khejri trees and small fruit yielding *Ziziphus nummularia* are found grown in association with rainfed crops. *Ziziphus nummularia* is used for its leaves as fodder for camel and goats and berries for edible purposes. *Acacia tortilis, A. nilotica, A. senegal, A. leucophloea, Capparis decidua, Tecomella undulata, Salvadora persica* and *S. oleoides* are other common trees found on various grazing lands or as sand stabilizers. *Calligonum polygonoides* is another interesting bush in Bikaner region. *Lasiurus sindicus* and *Cenchrus ciliaris* are prominent grasses in grazing fields as well as in sand dunes. In arid regions of Western India, introduction of compatible fuel, fodder and fruit trees in pastures as in agricultural fields acts as an insurance against frequent crop failures, and trees play a pivotal role towards peoples' survival and sustenance in such fragile ecosystems. Thus, trees have a very important place in the life of people in the arid zone of India, as they are directly related to the livelihood of inhabitants, and also provide the important service of climate moderation in an inhospitable environment (Sharma and Gupta 1996).

7.1 Agri-silviculture

This is the most popular system in the water-stressed areas receiving rainfall between 200 and 400 mm year^{-1}. People protect the naturally germinated seedlings of useful trees like *Prosopis cineraria*, *Ziziphus nummularia*, *Tecomella undulata*, etc., which come up in the crop fields. Mixed cropping of pearl millet, moth bean, cluster bean and sesame is carried out under these trees. These trees do not compete with the crops but rather are complimentary in terms of improving the micro-environment. These trees give fodder, fuel, fruit, etc. even when crop fails during drought and thus provide sustenance to the farmer during drought. Khejri (*P. cineraria*) and pearl millet agroforestry are well known around the world (Fig. 15.4). In association with this wonder tree, there is no reduction of crop yield.

Fig. 15.4 Agri-silvi system of *Prosopis cineraria* and pearl millet in arid region of Rajasthan, India

In semiarid regions of Peninsular India, the systems are more complex as the problem of frost does not exist; therefore, a vast number of trees (both fruit yielding and MPTs) exist on agricultural fields. *Borassus flabellifer*, *Tamarindus indica*, *Acacia leucophloea*, *A. catechu*, *Casuarina equisetifolia*, *Cassia siamea*, *Eucalyptus tereticornis*, *Albizia lebbeck* and many others are frequent trees on farms. *Leucaena leucocephala* has also been adopted as a common hedgerow-crop in many areas.

7.1.1 *Prosopis Cineraria*-based Agri-silvi Models

In arid region of Thar Desert, *Prosopis cineraria* grows naturally and retained in field crops consisting of rainfed crops such as pearl millet (*Pennisetum typhoides*) and pulses, viz. green gram (*Vigna aconitifolia*), cluster bean (*Cyamopsis tetragonoloba*), moth bean (*Vigna aconitifolia*) and cowpea (*Vigna sinensis*). *Prosopis cineraria* is a phreatophyte, drawing water from aquifers usually 10–25 m deep and occasionally down to 60 m below soil surface. It has been observed that the development of *P. cineraria* was slightly reduced when grown with pearl millet, while it increased by 15–20% when associated with cluster bean. There is a good symbiosis between *P. cineraria* and arid legumes (Fig. 15.5). An experiment was conducted to evaluate the tree-crop interactions as affected by varying tree densities (1666, 833 and 417 stems per ha) with different intercrops: green gram, cluster bean, moth bean and pearl millet. This showed that, during the establishment phase, *P. cineraria* did not compete with the associated crops and its growth not affected by the intercrops (Gupta et al. 1998). At 4 years of age, 417 stems per ha (4 m × 6 m = 24 m^2 per tree) was found to be the optimum density. At a later stage, towards 10 years, the optimum density was found to be 220 trees per ha. Pulse crops were better suited than pearl millet with and without *P. cineraria* (Table 15.7).

Fig. 15.5 Agri-silvi system of *P. cineraria* and cluster bean in arid region of Rajasthan, India

Table 15.7 Grain and straw yields (kg ha^{-1}) of green gram and pearl millet with and without *P. cineraria*.

Prosopis cineraria	Green gram		Pearl millet	
Tree density (trees per ha)	Grain	Straw	Grain	Straw
417	153	1666	133	4330
278	162	1699	141	4430
208	193	1803	158	5420
Open field crop	180	1720	165	5470

Realizing the potential of *Khejri* in arid region, a new variety of Khejri (*Thar Shobha*) has been developed by Central Institute for Arid Horticulture, Bikaner, through bud grafting (Fig. 15.6). It tolerates extreme high (>48 °C) and low (−4 °C) temperature and aridity conditions. It is extremely drought tolerant and has high potential of production under rainfed condition of arid and semiarid area. It is the first variety of Khejri which can develop uniform plants and can easily be fit in farming system mode for systematic cultivation. The bud-grafted plants have vigorous growth and are thornless with high pod yield and biomass within 3–4 years of establishment. A 5-year-old bud-grafted plant can yield 4.25 kg *sangri* (Khejri green pods) and 6.25 kg *loong* (Khejri leaves) in a year with improved production technology.

7.1.2 *Ziziphus nummularia*-based Agri-silvi Model

Ziziphus nummularia, locally known as *pala* in arid zone of Rajasthan, is associated with rainfed crops such as green gram, cluster bean, moth bean and pearl millet in areas receiving less than 400 mm rainfall. Maximum leaf forage (169 kg DM

Fig. 15.6 Thar Shobha, a new variety of *Prosopis cineraria* raised by bud grafting, which yields pods and leaves within 3–4 years

ha^{-1} year^{-1}) from *Z. nummularia* plants is obtained in deep alluvial sandy soils locally known as ‘buried pediment’. Minimum yields (112 kg DM ha^{-1} year^{-1}) are observed in the shallow soils on the broad flattish rocky surfaces at the foot of mountain slopes, termed ‘lower pediments’ (Shankarnarayan 1984).

7.2 Windbreaks/Shelterbelts

Wind erosion, a high thermal regime and hot desiccating winds are some of the serious problems, which affect the establishment, growth and yield of crops in arid areas. A mixture of trees and shrubs planted across the wind direction helps in reducing the wind speed (Fig. 15.7). Evaporative demand studies conducted at CAZRI with three-row shelterbelts of *Acacia tortilis*, *Cassia siamea* and *Prosopis juliflora* as side rows and *Albizia lebbeck* as the central row were found effective in reducing wind speed and wind erosion. Micro-shelterbelts of tall-growing plants have also been found quite effective in providing protection with about a 20 to 40% increase in yield of vegetable crops grown with irrigation (Sharma and Gupta 1997). In Bikaner region, rows of *Eucalyptus camaldulensis* and *Dalbergia sissoo* also act as effective shelterbelts and tree screens for creation of ‘microclimates’ in canal-irrigated areas (Fig. 15.8). Shelterbelts reduced the wind velocity by 20–46% on the leeward side for 2H–10H during the monsoon period (H, height of shelterbelt) (Sinha 1993).

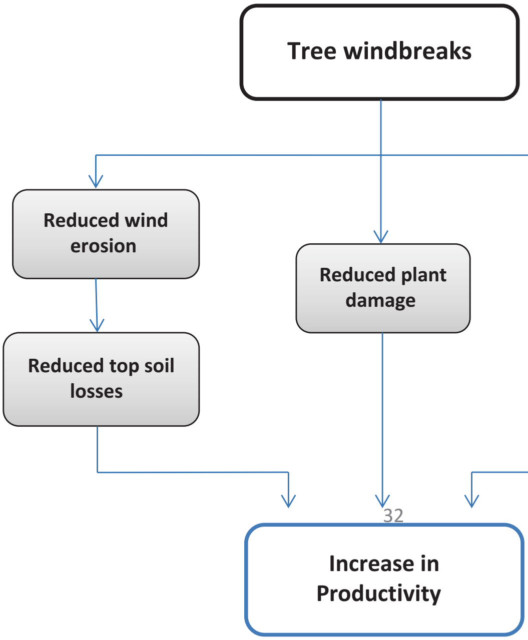

Fig. 15.7 Positive effects of tree windbreaks

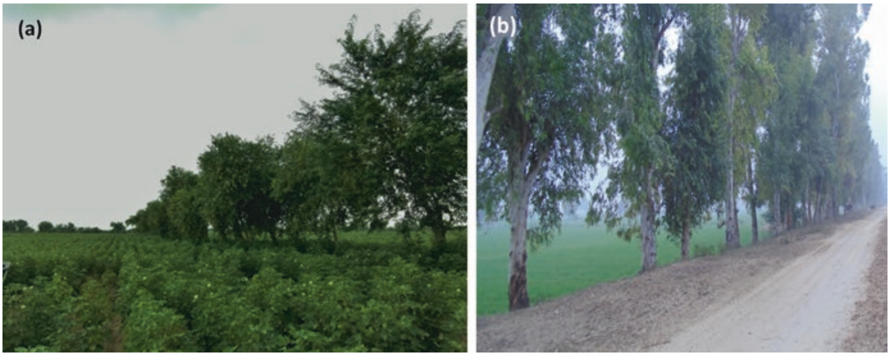

Fig. 15.8 Shelterbelt of (**a**) *Dalbergia sissoo* and (**b**) *Eucalyptus camaldulensis*

7.3 Fodder Production Models

Fodder trees play an important role in reducing the fodder shortage problem in India. In most parts of the country after the end of rainy season, animals suffer badly due to lack of protein-rich diet since availability of green fodder becomes scarce. The situation becomes serious during the dry season in water-stressed areas, when generally no crop can be grown and natural pasture, grasses and weeds become unproductive. Farmers either feed their animals with the low-quality hay of the stored crop residues or they travel long distances to gather green grasses or fodders. In such circumstance, shrubs and fodder trees are able to withstand the drought, stay green and provide a nutritious fodder for livestock. Alarming shortages of forage can be solved partially by planting fodder trees capable of sustained production of palatable forage high in protein and total digestible nutrients. Through the plantation of these species on degraded lands under silvipastoral systems and in farmer's fields under various agroforestry systems, fodder availability can be enhanced. Lopping of *Prosopis cineraria* in Western Rajasthan and *Albizia lebbeck*, *A. procera* and *Azadirachta indica* in Northern and Central India for leaf fodder and use of pods of *A. nilotica* and *P. juliflora* for fodder are common practices since old days. Most of these species are important source of fodder during lean period as well. Advantages of tree fodder are that trees can be grown on steep, rocky mountain slopes, in arid, saline or waterlogged soils and in areas with severe climatic conditions. Furthermore, trees do not need heavy inputs of fertilizer, irrigation, labour, pesticides, etc., as are generally needed to grow conventional fodder crops. Trees use and recycle nutrients that are beyond the reach of grasses and other herbaceous plants. Trees that accumulate nitrogen enhance forage quality. Their relative deep root system can exploit deep moisture resources, and, using this and other strategies, trees are more tolerant to dry periods than pastures.

Many fodder production systems have been designed to produce sufficient foliage for livestock feeding particularly during the dry season. These production systems include various types of agroforestry silvipastoral systems, where trees, animals and pastures are deliberately combined to obtain benefits and services (Mathukia et al. 2016). In arid region of Nagaur (Rajasthan), Arya (2006) observed that Z. *mauritiana* and *C. ciliaris* were the best silvopastoral combination for maximum dry fodder yield (3633 kg ha^{-1}). Grass *C. ciliaris* had mean 4-year yield of 1840 kg ha^{-1} with fruit tree *Z. mauritiana*, followed by 1510 kg ha^{-1} with *Acacia nilotica*, and 1240 kg ha^{-1} with *Ailanthus excelsa* (Table 15.8). The root system of

Table 15.8 Mean yield of *Cenchrus ciliaris* dry matter (kg ha^{-1}) and total fodder yield (kg ha^{-1}) in a silvopastoral system in the Nagaur district of Rajasthan, India

	Grass yield					Total fodder yield
Species	1997–1998	1998–1999	1999–2000	2000–2001	Mean	
Ziziphus mauritiana	1017 (100)	624 (41.5)	2655.5 (23.5)	3077 (307.7)	1843.5^{a}	3633^{a}
Ailanthus excelsa	900 (100)	633 (33.3)	1504 (23.5)	1923 (76.9)	1240^{b}	2231^{b}
Acacia nilotica	817 (150)	833 (20.00)	2361 (1 76.3)	2019 (50.00)	1507^{c}	2931^{c}
Mean	911^{a}	697^{a}	2173^{b}	2340^{b}	–	–

Source: Arya (2006)

Values carrying different letters are significantly different at $p < 0.01\%$. Standard error of means is given in parenthesis. Total fodder yield = Dry grass + dry leaf yield

Z. mauritiana was better developed than the other species. Mean maximum grass yield (1843.5 kg ha^{-1}) was obtained with *Z. mauritiana* followed by *A. nilotica* (1507 kg ha^{-1}). Species-wise and year-wise rainfall variation resulted significant differences in grass yield.

In the water-stressed areas, where rainfall is below 200 mm $year^{-1}$, and with this rainfall, food production is very difficult. On the other hand, there are some grass species, e.g. *Cenchrus ciliaris*, *Lasiurus sindicus*, etc., which are very well adapted to such climate and make natural rangelands. The climax tree species like *Prosopis cineraria* and *Ziziphus nummularia* naturally come up in these rangelands and make a silvopastoral system. Animals like cows, goats and sheep are the part of this farming system. Traditionally the areas near holy places like temples are kept reserved for silvipasture with very well-established social fencing. This is a very good example of sustainable management of common property resources that still exist in several places. The silvipastoral systems are strictly used according to the land's carrying capacity. Also these systems cover large areas, i.e. 100–500 km^2. These systems have low productivity but are an example of an excellent synergism between the nature and the natives, and that's why they have been sustained for centuries (Shankarnarayan et al. 1987). In Central India, *Dalbergia sissoo*, *Acacia nilotica*, *A. eburnea*, *A. leucophloea*, *A. catechu*, *Albizia lebbeck*, *Azadirachta indica*, *Butea monosperma*, *Pongamia pinnata* and *Holoptelea integrifolia* form important constituents of a silvopastoral system.

7.3.1 Fodder Bank Systems

In the areas, where fodder obtained from arable land is not sufficient to maintain the livestock, the inhabitants largely depend upon the forest-based fodder resources. Fodder banks are developed by using both indigenous and introduced fodder species (trees, shrubs and grasses). The basic idea behind this is besides getting fodder we must also ensure conservation of biodiversity while, providing nutritious fodder to livestock. A fodder bank is meant to provide protein supplementation, and hence the management practices are geared to maximizing the proportion of legume in the fodder bank at the end of the growing season. The fodder bank should also last for several years to cover the costs of establishment.

Silvopastoral system is the most prevalent system of arid regions of Rajasthan, where due to scanty rain crop production is risky and unremunerative. Livestock husbandry is important in the economy of the region. Under intensive grazing, the newly sprouted branches spread horizontally and provide feed to small animals such as goat and sheep. Gupta (1982) calculated that the average net annual returns per ha from silvopastoral system had been more than from the raising of the annual crops and *P. cineraria* was found to be most remunerative tree after *Ziziphus* spp. The harvested biomass of trees/shrubs is stored as fodder bank by weaker section of the society to feed their livestock during stress period. Potential species for this purpose are Khejri (*P. cineraria*), *bordi (Z. nummularia)* and *phog* (*Calligonum polygonoides*). After lopping, the leaves of *P. cineraria* and of *Z. nummularia* called

Fig. 15.9 *Calligonum polygonoides* entire plant (left) and leaves (*lasu*) collected and stored (right) for future use of animals

loong and *pala*, respectively are stored to feed the livestock during scarcity period. Every part of *phog* is having economic value. It is a good sand binder. The leaves (phyllodes) of *phog* called *lasu* are stored as fodder bank and used as animal feed (Fig. 15.9); floral buds called *phogla* used by local inhabitants in *raita* (a dish made with butter milk) and roots are used for making excellent quality charcoal. The leaves have anti-inflammatory and antiulcer properties.

In transitional rainfall zones, the trees are planted as close as 1 m × 1 m and are cut regularly to induce maximum herbage production. The cut herbage is usually carried to animal feeding stalls; sometimes sheep or goats are brought to the plots and allowed to forage on the cut branches of naturally growing fodder. The system is called fodder bank, which provides reserve fodder when it is in short supply, usually in the dry season. Trees such as species of *Ficus*, *Prosopis*, *Acacia*, *Cassia*, *Albizia*, *Feronia* and *Ziziphus* may find a place for these banks.

7.3.2 Three-strata Forage System

This is another type of fodder bank. It involves the planting of forages, shrubs and trees to form three canopy layers or strata in a unit of land. Pasture grasses, vines and herbs occupy the lower strata, shrubs occupy the middle strata and trees occupy the upper strata. The combination of grasses and trees can ensure year-round supply of fodder. This is more common in semiarid regions of southern India. The example of three-strata forage system is forage system (grasses and ground legumes), shrubs (*Z. nummularia*, *Gliricidia sepium, Leucaena leucocephala*) and fodder trees (*P. cineraria*, *Ficus poacellii, Lannea coromandelica,Hibiscus tiliaceus*).

7.3.3 Live Fence or Boundary Systems

Single or double rows of fodder trees/shrubs are planted along farm boundaries. The trees have the dual purpose of providing fodder and serving as live fence posts. If intended to enclose animals, the trees are usually planted densely, as in hedges, to

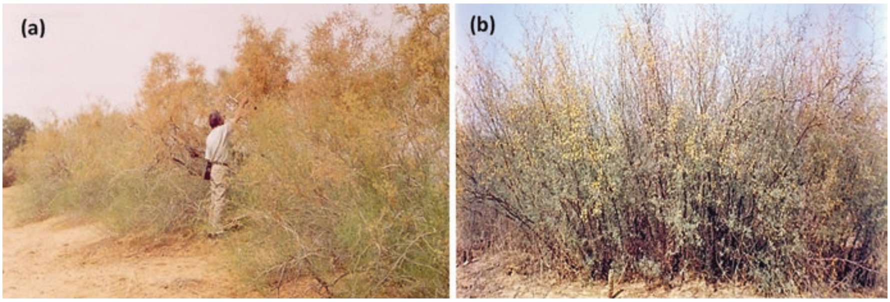

Fig. 15.10 Live fence of (**a**) phog (*Calligonum polygonoides*) and (**b**) Bawali (*Acacia jacquemontii*) in arid region of Bikaner (Rajasthan)

Fig. 15.11 Hedgerow intercropping system of *Dichrostachys nutans* + *Cenchrus ciliaris*

prevent animals from getting out. In some cases, thorny species (*Acacia jacquemontii*) are planted as thick hedges to prevent livestock from straying into crop plots and also to fence them off from wild animals. Live fences can be permanent or semi-permanent structures, and different species of plants are suited to this purpose. Highly productive fodder species recommended for this system include fodder beet (*Beta vulgaris*), elephant grass (*Pennisetum purpureum*), *Sesbania sesban*, *Leucaena leucocephala*, etc. In arid region, the live fence of phog (*Calligonum polygonoides*), Bawali (*Acacia jacquemontii*) (Fig. 15.10) and Arni (*Clerodendrum phlomidis*) proves promising.

7.3.4 Hedgerow Intercropping Systems

Fodder trees, mostly leguminous, are planted as hedges in single, double or triple rows. The spaces in between hedgerows are planted with pasture grasses. As in fodder banks, herbage may be cut and carried to animal feeding stalls. The more common practice is to let the animals forage on the cut tree branches and pasture grasses. *Dichrostachys nutans* + *Cenchrus ciliaris* are the best example of hedgerow intercropping system (Fig. 15.11).

Fig. 15.12 Traditional silvopastoral system for animal grazing in arid zone

7.3.5 Tree Plantation + Animal Grazing Systems

The community and village grazing lands in Rajasthan are called ‘oran’ or ‘bir’. *P. cineraria* and *Z. nummularia* form the major component of orans. When cut above the ground level, *Z. nummularia* produces many new shoots and branches which in a year form a bushy or cushion structure due to continuous grazing. The understorey of tree plantations contains local grasses and is utilized as grazing area for cattle, sheep and goats. The plantation may be of forest trees, fruit trees, etc. The livestock is allowed to graze freely on traditional and improved pasture grasses planted under trees (Fig. 15.12).

7.3.6 Indigenous Cut-and-carry Systems

As the name implies, the fodder is cut and carried to animal stalls. Farmers have long been practicing this system. Indigenous legumes such as species of *Prosopis*, *Ficus*, *Acacia*, *Leucaena*, *Gliricidia* and *Albizia* are the most preferred fodder tree species. Among grasses, *Lasiurus sindicus* and *Cenchrus ciliaris* are preferred pasture species in arid region (Fig. 15.13). Pearl millet and sorghum are frequently cut and carried for fodder. The research carried out to bring the grasses in farming system models through strip cropping suggests that in water-scarce arid region of Rajasthan, the strip cropping of grasses (*C. ciliaris*), under cut-and-carry systems with annual legumes such as cluster bean (*Cyamopsis tetragonoloba*) in 5:15 m ratio, produced highest system productivity (Soni et al. 2013b). Bhati et al. (2008) observed the highest benefit: cost ratio of 1.87 in strip-cropping system of grass and crops.

Fig. 15.13 A well-developed pasture of *Cenchrus ciliaris* under cut-and-carry system at CAZRI, RRS, Bikaner

8 Potential for Improvement and Way Forward

Agroforestry, like any single-cropping strategy, will not prove to be the silver bullet to climate change adaptation, mitigation and food security. However, agroforestry practices do have substantial potential to help smallholder farmers and pastoralists improve their well-being and the environmental sustainability of their farms and landscapes. By adopting the recommendations outlined below, we believe that agroforestry can be a cornerstone of climate-smart agriculture and contribute, as a part of larger development, initiatives, helping those who depend upon agriculture for their livelihoods and to better adaptation to future climate change. The policy framers must provide an enabling legal and political environment with an overarching national plan, appropriate institutions and effective and transparent governance structures that coordinate between sectorial responsibilities across national to local institutions. Improved market accessibility and development of markets for ecosystem services provided by agroforestry to enhance income-generating opportunities must be at place. This can be achieved through improving infrastructure or more locally through establishing cooperatives that pool resources to access markets. Involvement of farmers and pastoralists in the project planning process is very important. We must improve access to knowledge and germplasm. This will significantly improve farmers' willingness to plant or cultivate more trees for multiple purposes. Farmer to farmer dissemination and educational visits provide potential alternative mechanisms and increase adoption rates. We must improve land and tree tenure. This can have a significant effect on farmer's willingness to invest in their land and improve productivity. Reducing state regulation of farmer management and harvesting and selling of trees on their own farms are important reforms needed.

Many improved management practices provide benefits to farmers only after considerable periods of time. This can be prohibitive for poor households because investing in new practices requires labour and incurs costs that must be borne before the benefits can be reaped. Payments for carbon sequestration is an appropriate way of covering the time lag between investing in climate-smart practices and obtaining the environmental and economic benefit. We must improve access to farm implements and capital. Credits, loans and other forms of access in establishing agroforestry systems can significantly reduce farmers' difficulties.

During the last more than three decades, many agroforestry technologies have been developed and demonstrated by the research organizations. But most of them have not reached to farmers' fields for want of awareness, inadequate infrastructure and lack of policy support. Therefore, the desired impact has not been observed in terms of adoption of technology, particularly related to agroforestry. However, policy issues related to agroforestry as such have not been taken up for research studies. But in discussion in various meetings, seminar, workshops and symposia, these issues have always found place. It is well-known fact that the growth and development of agroforestry are influenced by various policies of the economy like credit, trade, taxation, power, transport, market, etc. These policies influence the agriculture sector either directly or indirectly besides the core forest and agricultural policies which have a larger bearing on the agroforestry program in the country. State regulations and permit systems for felling of trees and for timber transportation have been main interferences in marketing of timber grown on farmers' land by private investment and have been major discouragement to the expansion of agroforestry; besides, marketing of agroforestry produced is not organized. Thus, a consensus emerged recently that India needs urgently a policy on agroforestry. The initiative for a National Policy on Agroforestry in India was taken at the same time when FAO was preparing guidelines for decision-makers for advancing agroforestry on the policy agenda (FAO 2013). After long deliberations and discussion, India launched a forward-looking National Agroforestry Policy in 2014. However, to implement the same appropriate guidelines for production of quality planting material and supply system and coordination, convergence and synergy between various sectors linked with agroforestry will be required. This will require adequate research interventions and support as well as trained manpower.

9 Conclusions

The agroforestry technologies developed based on research and development work in India have a considerable potential to meet the challenges in the current scenario of climate change. A number of technologies with suitable tree and crop combinations have been identified for different agroecological zones of the country including dry regions. The technologies provide option for livelihood, environmental and energy security. There is further need to upscale these technologies to achieve the desired targets. Special attention is needed in dry land agriculture, which is mainly dependent on livestock-based economy, which in turn depends on agroforestry-based systems.

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Chapter 16
Agroforestry for Rehabilitation and Sustenance of Saline Ecologies

R. Banyal, Rajkumar, Manish Kumar, R. K. Yadav, and Jagdish Chander Dagar

Abstract Saline soils constitute 15% of global landmass and have direct influence on the production functions of the existing land uses. In India, 6.75 Mha area is salt-affected, out of which 2.92 Mha are saline soils. The menace, increasing with each passing year to the irrigated areas, has become a major concern. Agroforestry plays a pivotal role in biological amelioration and check in further expansion of such landmasses. It is always useful to have agroforestry models/systems for saline landmasses by involving multipurpose nitrogen-fixing tree species, fruit trees, halophytes, and arable crops of economic importance. The potential flora suitable to saline soils has been identified based on tolerance level and climatic adaptability. The successful planting methods, viz., ridge-trench, furrow, and subsurface planting with furrow irrigation, have also been assessed and recommended for saline soils. Plant adaptations to saline conditions involve complex physiological traits, metabolic pathways, and molecular gene networks. These adaptive mechanisms to such ecologies are basically governed by one of the three processes like exclusion, excretion, and accumulation among trees and/or crops. In true sense, reclamation processes also help to keep the salt away and/or within tolerable limits for growing flora in the rhizosphere. Productive service functions of plants can be obtained from saline soils by combining reclamation and management options in pragmatic way. Sequential, agrisilviculture, agrihorticulture, silvopastoral, multipurpose wood lots, saline aquaforestry, homestead gardens, and energy plantations are the biological and economical viable recommended farm agroforestry practices in saline soils. *Prosopis cineraria* (Khejri) for hot dryland, *Eucalyptus tereticornis* (Safeda), *Melia composita* (Dek), *Aegle marmelos* (Bael), *Emblica officinalis* (Aonla), and *Carissa carandas* (Karonda) for saline-irrigated area and *Casuarina equisetifolia* (Casuarina), *Eucalyptus camaldulensis* (Safeda), and *Acacia nilotica* (Babul) for

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coastal regions as agroforestry trees in system mode are successful in reclaiming the saline soils with economic gains for sustenance. The benefits of agroforestry can be grouped into biomass, soil/environment, and socioeconomic outputs. This chapter highlights the issues in the quantification of the systems' output in terms of existing procedural protocols. The agroforestry has passed and transcends into variable phases with the advancement as subject. Therefore, plausible future of the agroforestry is presented by taking the cognizance of present needs and future challenges in general and particular about saline soils. The holistic approaches of agroforestry undoubtedly rehabilitate saline soils and certainly will give income in perpetuity, employment generation, food and nutritional security and environmental safety for inhabiting masses in arid and semiarid regions.

Keywords Agroforestry · Climate moderation · Rehabilitation · Saline soils · Sustenance · Evaluations

1 Introduction

Salinity is an aggravating problem in many parts of the world especially in arid and semiarid regions. This can be directly linked with the significant yield losses incurring from the existing land uses. A major threat to world agriculture involves production of 70% more food for an additional 2.3 billion people by 2050 worldwide (FAO 2009). Approximately 76 Mha salt-affected lands are affected by human-induced salinization and sodification (Olderman et al. 1991). The rate of salinization and sodification expansion is between 0.25 and 0.50 Mha annum^{-1} (FAO 2000). Agricultural productivity is directly governed by osmotic and specific ion effects in saline soils (Yadav et al. 2007; Munns and Tester 2008) and deterioration of physical properties in sodic soils (Abrol et al. 1988). Conventional agricultural practices are not economically feasible on such soils because of expensive inputs which prohibit the farmers to go for cultivation, especially arable crops (Qadir et al. 2002). Keeping in view the world scenario, in terms of catering to the demand from existing resources, it is imperative to explore the possibility and options for rehabilitating such degraded soils and bring them under productive cultivation. The methods for rehabilitation of such ecologies involve hydrological, agronomic, and/or phytoremediation practices. Hydrological and agronomic practices are cost and labor intensive and need developmental strategies for their result-oriented implementation. On the other hand, phytoremediation can be a low cost easily executable option without any significant problems. Plants on their adaptive evolution against salinity can be classified into two major types: the halophytes (that can withstand salinity) and the glycophytes (that cannot withstand salinity and eventually die). Majority of the crop species belong to the glycophyte category. Thus, salinity becomes one of the most brutal environmental stresses that hampers crop productivity with serious ecological security concerns worldwide (Munns and Tester 2008). Though salinity can be hostile even to woody tree species, these are known to tolerate abiotic stresses better than annual species (Dagar and Yadav 2017). However, recent research efforts have greatly improved understanding of biology and management of woody plantations for improved productivity of saline environments (Dagar et al. 2016a). Therefore, forestry and agroforestry systems are the potential alternative land use options for saline ecologies.

The focus of this chapter is to compile and synthesize the available information in rehabilitation of saline wastelands through tree cultivation alone or integrating them with arable crops to achieve the goal of ecological and economical sustenance. The efforts are also aligned to address the current and future challenges in the eye of agroforestry approaches for farm diversification at large and economic sustenance in particular. The current and future challenges in agroforestry systems evaluations with headway road map is also duly highlighted and discussed with reference.

2 Salt-affected Soils

Salt-affected soils are grouped according to the nature of plant response to the presence of soluble salts and the basis of management practices required for their reclamation. Unlike the pedogenic system, it is a simple system of classification requiring information on the nature of soluble salts only. Salty soils are grouped into two broad classes based on the assumption that salts are either neutral or alkaline in reaction. Basically, these are saline and/or alkaline in nature and if we go in detail, the third category of saline-sodic is also there. Here, this chapter is restricted to rehabilitation of only saline soils and so the alkalinity of the soil is beyond the scope of this chapter.

2.1 Saline Soils

These soils with white salt encrustation on the surface (Fig. 16.1) have predominantly chlorides and sulfates of Na, Ca, and Mg. The soils with neutral soluble salts have saturation paste pHs < 8.2, but the electrical conductivity (ECe) of saturation paste extract is generally more than 4 dS m^{-1} at 25 °C. Such soils invariably have <15 sodium absorption ratio (SAR) of soil solution.

The main characteristics of saline soils are:

- *Chemically* saline soils have an electrical conductivity (ECe) of 4 dS m^{-1} or more with dominance of chlorides and sulfates of Na, Ca, and Mg and pHs always <8.2.
- *Physically* saline soils are stable in structure and permeable to water and air with other physical characteristics like normal nonsaline soils.
- *Plant growth*: High osmotic pressure of soil solution and toxicity of specific ions (Na, Cl, etc.) are the reasons of poor plant growth in saline soils.

Fig. 16.1 Saline soils showing white salt encrustation on the soil surface

- *Management*: Leaching and drainage are the options for its efficient use in production functions.
- *Distribution*: Mainly distributed in arid and semiarid regions.
- *Groundwater quality*: High electrolyte concentration and SAR are groundwater quality issues in saline soils.

Saline soils usually remain flocculated due to the presence of excess salts. Inland, coastal, and deltaic are the location-specific broad groups of saline soils in India (Sharma 1998). Inland saline soils of arid and semiarid regions contain neutral salts and distributed in areas with <550 mm rainfall. The maximum salt accumulation under excessively desiccating conditions happens to be in the surface horizon with shallow water table. Under such situations, soils often remain waterlogged or even submerged for some duration of the year. In India, these soils are generally distributed in parts of Haryana, Punjab, and Rajasthan representing arid and semiarid regions of the country. Saline-alkali soils of Indo-Gangetic alluvium are mostly confined to regions with around 550 mm mean annual rainfall in the form of a narrow geographic band separating the alkali and saline soils. In these soils, there is preponderance of neutral salts but also contains sizeable quantity of sodium carbonates and bicarbonates. These are sandy to loam in texture and may have calcic or petrocalcic horizon in the substratum. Inland saline soils of subhumid regions contain 23–40% calcium and magnesium carbonates in fine powdery form. In this category, some soils may also contain sizeable quantity of sodium carbonate and bicarbonates and thus designated as saline-alkali soils. However, there is predominance of neutral salts in such soils. These are widespread in parts of East Champaran, West Champaran, Muzaffarpur, Saron, and Saharasa districts of Bihar. Inland salt-affected medium and deep black soils (Vertisols) exist mainly in parts of Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Telangana, Gujarat, and Karnataka. Salinization in Vertisols is associated with introduction of canal irrigation and subsequent rising water table. Medium to deep black saline soils of deltaic and coastal semiarid region generally contain only neutral salts with traces of bicarbonates. These soils are found in deltas of Godavari and Krishna rivers and along the Saurashtra coast in Gujarat. Saline micaceous deltaic alluvium soils of humid region have neutral salts which owe their origin to saline substratum and saline water inundation during marine cycles and origin of delta. The deep micaceous, fine-textured soils of Ganges delta in the humid subtropical climatic region are saline to varying degrees with perpetual shallow saline water table. Such soils have the maximum salt accumulation on the surface with preponderance of chlorides and sulfates of sodium, magnesium, and calcium with minor quantity of bicarbonates. Saline-humic and acid sulfate soils of humid and tropical regions found to be humus-rich saline soils occupying marshy situations occur along the Malabar Coast. These soils remain submerged from May to December and seawater inundation under tidal cycles during the subsequent lien months. The salient features of such soils are ochric epipedon; humic horizon in the substratum of some soils; signs of gleying, reduction, and bleaching in the soil matrix; high EC throughout the profile; soil pH in the acidic range; high to very high content of organic matter; and shallow saline water table. These soils have apparently developed under the impact of marine cycle. Saline marsh of Rann of Kutch constitutes the vast saline marsh and contains a variety of saline soil types.

3 Extent of the Problem

The total area of salt-affected soils in the world is 831 Mha which includes 397 and 434 Mha of saline and sodic soils, respectively. It constitutes about 15% of the global land area and found to be distributed in Asia and the Pacific, Australia (8%), Europe (3.6%), and Latin America (2.5%) (FAO 1997). Tanji (1995) reported that 19.5% area suffered from saline seepage in dryland agriculture and secondary salinization in irrigated agriculture land areas.

In India, divergent estimates ranging from 7.0 to 26.0 Mha salt-affected lands were given by several agencies mainly the Ministry of Agriculture and Farmers Welfare (MoA and FW), National Remote Sensing Agency (NRSA), National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Indian Council of Agricultural Research-Central Soil Salinity Research Institute (ICAR-CSSRI), etc. But 6.75 Mha land area is the widely accepted figure (Table 16.1) for the quantum of the salt-affected land masses in the country (Mandal et al. 2010). It is estimated to increase up to 20 Mha by the mid of this century (CSSRI 2013). The total area under alkali/sodic and saline soils in the country is 3.83 and 2.92 Mha, respectively.

The area statistics showed that 80% of salt-affected soils are associated with arable cropping, 18% coexisted with erosion, and 2% is in the forest-covered areas. These soils currently occupying 2% of the geographical area of the country and constitute 4.2% of the arable land area, and a considerable area is under irrigated cropping in various canal commands and groundwater irrigation. Saline soil comprises of 44% of the total salt-affected soils (saline, sodic, and saline/sodic) in the country and spreads in 12 Indian states and islands. These are slight (44%), moderate (26%), and strongly (18%) saline in nature. Out of 2.92 Mha, 1.75 Mha

Table 16.1 Extent of salt-affected soils in India (000 ha)

State(s)/union territory	Sodic	Inland saline	Costal saline	Total
Andaman and Nicobar Islands	–	–	77.0	77.0
Andhra Pradesh and Telangana	196.6	–	77.6	274.2
Bihar	105.9	47.3	–	153.2
Gujarat	541.4	1680.6	–	2222.0
Haryana	183.4	49.2	–	232.6
Jammu and Kashmir	17.5	–	–	17.5
Karnataka	148.1	1.3	0.6	150.0
Kerala	–	–	20.0	20.0
Madhya Pradesh	139.7	–	–	139.7
Maharashtra	422.7	177.1	7.0	606.8
Odisha	–	–	147.1	147.1
Punjab	151.7	–	–	151.7
Rajasthan	179.4	195.6	–	375.0
Tamil Nadu	354.8	–	13.2	368.0
Uttar Pradesh	1347.0	22.0	–	1369.0
West Bengal	–	–	441.3	441.3
Total	3788.2	2173.1	783.8	6745.1[a]
	Say 6.75 million ha			

Source: Modified from Mandal et al. (2010) and Dagar (2014)
[a]Exact figures slightly differ because of rounding of the data

are in inland plains with poor-quality groundwater in arid/semiarid regions, and 1.2 Mha in east and west coastal plains intercepted by seawater intrusion with humid climate. Among the inland plains, saline soils are confined to the arid and semiarid areas of Gujarat (17%), Rajasthan (6.6%), Maharashtra (5.9%), Karnataka (0.06%), Haryana (1.6%), and Bihar (1.6%) states (Sharma et al., 2015). In the island areas, these are strongly saline and located in the south and middle Andaman and North Andaman and Mayabunder. If one looks at the state-wise tally, the problem of salinity in Punjab and Haryana may not be much in extent, but losses in food grain production scales up to one million tons for every 0.1 Mha going out of cultivation which is crucial for getting higher productivity in the region. Moreover, even a loss of 0.1 Mha directly affects the livelihood and living standard of approximately one million people (Gupta 2015).

4 Selection Criteria of Tree Species for Afforestation in Saline Soils

The choice of proper tree species depends upon the local agro-climate, land capability, purpose of planting, tolerance to salinity, and waterlogging/drought. In general, plantations for fuel wood were rated better for salty soils than the timber wood tree species in earlier days. But with the change in time, the objectivity of afforestation on such soils has also changed. Now, the recent efforts are on the exploration of tree species which also should give timber and environmental benefits, even though the salinity tolerance level changes with growth stages of the tree species. Socioeconomic aspects with ameliorative role of trees are the priority of the current times in selection of trees for afforestation on saline soils. Numerous tree species have been evaluated for their tolerance to salinity. Among them, some principal species of arid and semiarid regions rated better than the others have been recommended for cultivation in saline conditions. The list of promising tree species with their agroclimatic requirements growing under saline or in waterlogged conditions is presented in Table 16.2.

The tree species adapting to the salinity should also have the following other benefits:

- Capability to grow in salty conditions with tolerance to frost and occasional flooding.
- High water and nutrient use efficiency.
- Resilience against climate changes by providing income during extreme climate and protection of agriculture crops.
- Reduce salinization, arising due to various climatic factors, by creating better microclimate conditions.
- Greater potential for CO_2 sequestration in saline soil.
- Perennial in nature, easy to establish and manage in saline conditions.
- Fast growing with capacity to pollard and coppice for realizing quick returns.
- Multipurpose to cater the demand of firewood, timber, food, fodder, fiber, edible or nonedible oils, medicinal products, paper pulp, ability to fix atmospheric nitrogen, etc.
- Drought resistant as sometimes high salt concentrations in soil may cause physiological drought.
- Do not have allelopathic effect.
- Capacity to improve physical, chemical, and biological properties of soils through addition of organic matter and creation of better microclimatic conditions.
- Fast decomposition rate to increase soil CO_2 for dissolution of native $CaCO_3$ in soil.
- Capable of producing a prolific root system to facilitate drainage from waterlogged saline soils to drawdown the groundwater table with reduction in salt accumulation in soils.
- Helpful in checking soil erosion.
- Species should be in the farmers' perspective point of view.

The promising tree species which performed better in saline soils with saline irrigation up to ECiw 12 dS m^{-1} are listed in Table 16.3. Tree species are categorized as very promising, promising, and poor performer. Such categorization is helpful in devising the strategies to rehabilitate saline soils through afforestation and agroforestry approaches.

Table 16.2 Relative tolerance of tree species for saline soils (ECe dS m^{-1})

Range of tolerance (EC dS m^{-1})	Agroforestry (forest/fruit) trees/shrubs	Common name	Rainfall (mm)	Drought resistance	Nitrogen fixation
Very high saline (20–30)	**For inland saline soils**				
	Prosopis juliflora	Mesquite	150–750	High	Yes
	Parkinsonia aculeata	Parkinsonia, Jerusalem thorn	–	–	–
	Salvadora oleoides	Jaal	300–600	High	No
	Salvadorapersica	Jaal	300–600	High	No
	Acacia farnesiana	Pissi babul	300–700	High	Yes
	Suaeda fruticosa	Suaeda	–	–	–
	Suaeda maritima	Suaeda	–	–	–
	Haloxylon spp.	Haloxylon	–	–	–
	Atriplex spp.	Atriplex	–	–	–
	Tamarix articulata	Fransh	100–700	High	No
	Tamarix troupi	Fransh/Jhau	100–700	High	No
	Tamarix ericoides	Fransh/Jhau	100–700	High	No
	For coastal saline soils				
	Avicennia marina, A. officinalis	Avicennia	–	–	–
	Rhizophora apiculata, R. mucronata, R. stylosa	Rhizophora	–	–	–
	Bruguiera gymnorrhiza, B. parviflora	Bruguiera	–	–	–
	Ceriops tagal	Ceriops	–	–	–
	Acanthus ilicifolius, A. volubilis	Acanthus	–	–	–
	Aegiceras corniculata	Aegiceras	–	–	–
	Excoecaria agallocha	Excoecaria	–	–	–
	Heritiera fomes, H. littoralis	Heritiera	–	–	–
	Nypa fruticans	Nipa palm	–	–	–
	Sonneratia alba, S. caseolaris	Sonneratia	200–2000	Moderate	Yes

	Casuarina equisetifolia	Casuarina, Saru	–	–	–
	Barringtonia asiatica	Barringtonia	–	–	–
	Clerodendrum inerme	Clerodendrum	–	–	–
	Pandanus spp.	Pandanus	300–700	Moderate	Yes
	Pongamia pinnata	Papri	–	–	No
	Cordia subcordata	Lasura, Cordia	400–1500	Moderate	No
	Terminalia catappa	Terminalia	–	–	–
	Calophyllum inophyllum	Calophyllum	–	–	No
	Ficus retusa	Ficus	–	–	–
	Manilkara littoralis	Manilkara	–	–	–
	Thespesia populnea	Thespesia			
Highly saline (14–20)	*Prosopis cineraria*	Khejri	150–750	High	Yes
	Acacia tortilis	Israeli kikar	–	–	–
	Acacia nilotica	Pahari kikar	200–1500	High	Yes
	Acacia pennatula	Kikar	–	High	Yes
	Casuarina glauca	Casuarina, Saru	200–2000	Moderate	Yes
	Casuarina obesa	Casuarina, Saru	200–2000	Moderate	Yes
	Eucalyptus camaldulensis	River red gum, Safeda	400–1500	Moderate	No
	Feronia limonia	Kainth, Kabit	–	–	–
	Ziziphus mauritiana	Ber	200–1000	High	No
	Acacia auriculiformis	Australian kikar	–	High	Yes
Saline (10–14)	*Acacia senegal*	Kikar	–	High	Yes
	Casuarina cunninghamiana	Casuarina, Saru	200–2000	Moderate	Yes
	Eucalyptus tereticornis	Mysore gum, Safeda	400–1500	Moderate	No

(continued)

Table 16.2 (continued)

Range of tolerance (EC dS m^{-1})	Agroforestry (forest/fruit) trees/shrubs	Common name	Rainfall (mm)	Drought resistance	Nitrogen fixation
Moderately saline (5–10)	*Albizia procera*	–	–	Moderate	Yes
	Dalbergia sissoo	Shisham	500–2000	Moderate	Yes
	Emblica officinalis	Aonla	–	Moderate	Yes
	Guazuma ulmifolia	–	–	–	–
	Punica granatum	Anar	–	Moderate	–
	Samanea saman	–	–	–	–
Less saline (<5)	*Acacia auriculiformis*	Australian kikar	–	–	Yes
	Acacia deamii	–	–	–	Yes
	Acacia catechu	Khair	200–1500	High	Yes
	Syzygium cumini	Jamun	300–850	Moderate	No
	Salix babylonica	Weeping willow	–	–	–
	Tamarindus indica	Imli	100–700	High	No
	Albizia lebbeck	Siris	400–1000	Moderate	Yes
	Leucaena leucocephala	Subabool	–	–	–
	Populus spp.	Poplar	–	–	–
	Melia azedarach	Dek, Bakain	300–800	Moderate	No
	Azadirachta indica	Neem	200–1200	Moderate	No
	Dendrocalamus strictus	Bamboo	–	–	–
	Butea monosperma	Palash	300–1000	Moderate	No
	Terminalia arjuna	Arjun	400–1500	Moderate	No
	Ailanthus excelsa	Maharukh	–	–	–
	Dalbergia sissoo	Shisham, Tahli	500–2000	Moderate	Yes
	Balanites roxburghii	–	–	–	–

Source: CSSRI (1995) and Dagar (2014)

Table 16.3 Performance rating of tree species with saline water irrigation (ECiw up to 12 dS m^{-1})

Performance ratings	Agroforestry (forest/fruit) trees/shrubs	Common Name
Very promising	*Acacia nilotica*	Desi kikar, babul
	Acacia tortilis	Israeli kikar
	Acacia farnesiana	Pissi babul
	Cassia siamea	Cassia
	Capparis decidua	Kair
	Eucalyptus tereticornis	Mysore gum, Safeda
	Eucalyptus camaldulensis	River red gum, Safeda
	Melia azedarach	Darek, Dek
	Melia composita	Dek, Bakain
	Prosopis juliflora	Mesquite
	Prosopis cineraria	Khejri
	Pithecellobium dulce	Jangli jalebi
	Phoenix dactylifera	Datepalm, Khajur
	Salvadora persica	Jaal
	Salvadora oleoides	Jaal
	Tamarix articulata	Faransh
	Tamarix troupi	Jhau
	Tamarix ericoides	Faransh/Jhau
Promising	*Azadirachta indica*	Neem
	Cassia javanica	Cassia
	Dalbergia sissoo	Shisham, Tahli
	Feronia limonia	Kainth
	Punica granatum	Anar
	Aegle marmelos	Bael
	Tecomella undulata	Rajasthani Sal
	Ziziphus mauritiana	Ber
	Ziziphus jujuba	Ber
	Salix spp.	Willow
Poor	*Acacia auriculiformis*	Australian kikar
	Bauhinia variegata	Kachnar
	Cassia glauca	Cassia
	Cassia fistula	Amaltash
	Pongamia pinnata	Papri
	Syzygium cumini	Jamun

Source: CSSRI (1995), Tomar et al. (2003), and Dagar (2014)

5 Afforestation Practices in Saline Soils

Creation of favorable environment for tree root establishment and growth in salt-affected soils needs special package and practices. There are different points which must be taken into consideration to make the success of plantations on such challenged ecologies. The comprehensive account of such points is discussed in this text and summarized as:

- Identification of nature and degree of salt problem
- Quantity and quality of available irrigation water
- Choice of the suitable tree species

- Selection of proper planting methods for afforestation activities
- Protection of plantations during the initial years of outplanting

Before going for plantation, it is essential to diagnose the nature and magnitude of the problem, i.e., salinity level in this case. Once the causative factors are established, exacting practices must be opted to carry out the successful plantation activities on such challenged landmasses.

5.1 Plantation Technology

Selection of proper planting technique is of utmost significance. The plantation techniques for afforestation in saline soils are mainly governed by site and soil conditions, species to be planted, and the purpose of plantation. There are several methods for planting on normal soils, but in case of saline soils, we have only left with limited options to make the plantations survive on such degraded areas. Only those methods are suited to saline soils which either eliminate or alleviate the constraints due to salinity especially during establishment of plantations. The technique should be such that the rainwater is utilized to the maximum possible extent, and the salt concentration in the active root zone of young seedlings is kept at a minimum level so that the adverse effect of high salinity is minimized. The traits which are desired in planting methods suited to saline soils are enlisted here as follows:

- Help in pushing the salts down to deeper soil layers through leaching.
- Reclaim more soil volume for proper root growth.
- Maintain low salinity in rhizosphere.
- Reduce water application cost.
- Help in *in situ* conservation of rainwater and at the same time alleviate waterlogging problems.
- Cost-effective.

The most promising planting techniques for afforestation of saline soils are ridge-trench, furrow, and subsurface planting methods, but other methods like pit and auger hole are also discussed here because sometimes these may be helpful in the plantation activities. The details of merits and demerits of each planting methods are discussed below.

5.1.1 Pit Planting

The objective of creating planting pits is to aerate and loosen the soil in which the plants will grow. When these planting pits are prepared, they should not be left empty with the excavated soil lying on the ground but refilled immediately; otherwise sun and wind will dry out the soil completely (Fig. 16.2).

Soil preparation can be carried out in patches and strips or by working the complete soil on the plantation area. Complete cultivation is necessary for tree and shrub

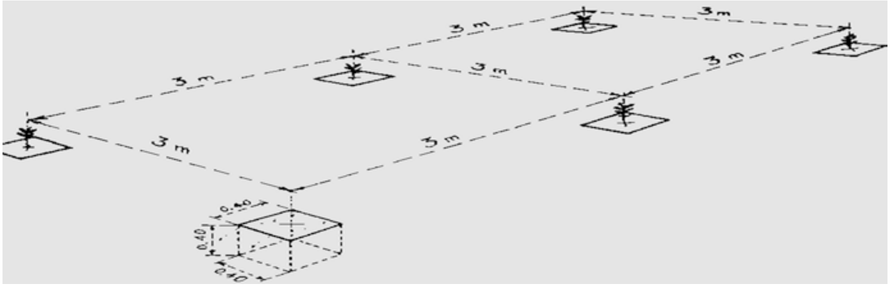

Fig. 16.2 Planting pits (40 cm^3) at a density of 3 m × 3 m (square planting)

species which are intolerant to competition from grass forte and woody growth. Sometimes, spot preparation may be sufficient but the spots should be large (e.g., 1–1.5 m in diameter). But it is important that the working of soil should be done thoroughly.

In pit planting method, salts get mixed up and distributed uniformly in the dug-out zone. Even the good soils used for back filling the pits turn saline within few months. Thus, pit planting method is an utter failure in saline soils. Salt distribution patterns suggest that salts do not move far away and deep into the profile. Most of the salts stay closer to the active root zone. Consequently, the plantation establishment and survival rarely exceeds 25% with this method in strongly saline soils (CSSRI 1995). A desirable feature for successful planting method in saline soil is that it should minimize the salt levels near the active root zone of trees.

5.1.2 Ridge-Trench Method

It is a usual practice in low-lying areas along the roads, railway lines, and canal embankments where water stagnates in burrow pits. Saplings are planted in the center of the ridge or close to edges of the ridge flats in staggered double-row planting system (Fig. 16.3). Ridges prepared in saline soils enhance salt accumulation on exposed surfaces of the ridges. Accumulation of salts on the berms and top of the ridges reduces the stability of ridges and make them highly prone to erosion during monsoon season. Requirements of spot irrigation and frequent repair of ridges increase the maintenance cost of plantations. Hence, ridge-trench planting method is only suitable for saline soils existing in waterlogged areas.

5.1.3 Post-auger Hole Planting

This planting method is suitable for breaking of hardpans generally found in alkali soils rich in crusts of $CaCO_3$. But this method is of significance in case of saline-sodic soils where salinity and hard $CaCO_3$ (*kankar*) layer coexisted. In this method,

Fig. 16.3 Ridge–trench planting

Fig. 16.4 Tractor-mounted auger hole (left) and view of pit (right)

bore holes of 15–30 cm in diameter are dug up to 120 cm or more with the help of tractor-mounted auger hole such that it pierces beyond the *kankar* layer for root facilitation (Fig. 16.4). The performance of post-auger hole planting method is quite satisfactory in field trials under alkali soil conditions. For high-value fruit trees, the pit size may be increased to 45 cm × 45 cm × 30 cm. The pit holes are interconnected with an irrigation channels in furrow landscape.

5.1.4 Furrow Planting

Furrow planting has been successful in establishment of tree saplings on saline soils (Dagar et al. 2016a, b). In this method, tractor is to be used for creating furrow to the size of 60 cm wide and 20 cm deep (Fig. 16.5). The saplings are to be planted at sill of the furrows. It is efficient in desalinization of the soil with the help of rainfall thus creating a favorable zone of low salinity below the sill of the furrow through the downward and lateral fluxes of water making salts move away from the root zone (Tomar et al.1998; Dagar et al. 2016a, b).

Fig. 16.5 *Eucalyptus tereticornis* plantations in furrow planting method in saline soils

5.1.5 Subsurface Planting and Furrow Irrigation Method (SPFIM)

This is improved version of furrow planting. The basic concept envisages that salinity is usually higher in the surface layers and decreases with depth down to water table in waterlogged saline soils**.** Soil moisture contents are minimum near the surface and maximum near the water table. Therefore, to take advantages of low salinity and better soil moisture regimes in subsurface layers, saplings are planted in polythene bag-sized holes made at the sill of the 15–20 cm deep irrigation furrows, such that roots are exposed in 20–35 cm soil layer from the original surface (Fig. 16.6). This method performed satisfactorily in large-scale field trials conducted on highly saline soils (CSSRI 1995; 2016; Dagar et al. 2016a, b). Furrows are subsequently used for irrigating saplings which help in pushing the accumulated salts to deeper soil layers and keep them away from the active root zone into the bed area between two furrows. Thus, large volume of soil remains relatively free of salts which greatly improve the survival and growth of tree saplings.

Among the entire range of plantation methods related to saline soils, only ridge-trench, subsurface, and furrow (Fig. 16.7) are found to be the best in arid and semi-arid regions with underlying saline groundwater. The published work (Yadav and Dagar 2016; Dagar et al. 2016a, b) equally supports the recommendations for these types of planting techniques to have better survival in saline landmasses.

6 Mechanism of Salt-tolerance in Plant System

Saline soils are not ever fully reclaimed in true sense, but the reclamation processes only keep the salt in the root zone within permissible/acceptable limits. Thereafter, the land needs to be managed by growing trees and/or crops alone or in combination

Fig. 16.6 *Eucalyptus tereticornis* plantations in subsurface planting and furrow irrigation (SPFIM) method in saline soils

for productive service functions. Therefore, it is imperative to manage saline soils in pragmatic way through mix of reclamation and management options. Plant adaptation or tolerance to salinity stress involves complex physiological traits, metabolic pathways, and molecular or gene networks. A comprehensive understanding on how plants respond to salinity stress at different levels and an integrated approach of combining molecular tools with physiological and biochemical techniques are imperative for the selection of salt-tolerant trees and crops (Yadav and Dagar 2016). Recent researches identified various adaptive responses to salinity stress at molecular and physiological levels; however, further investigations are needed for developing more comprehensive understanding for the mechanism responsible for it.

Soil salinity is known to repress plant growth in the form of osmotic stress and then followed by ion toxicity. During the initial phases of salinity stress, water absorption by root system decreases, due to osmotic stress of high salt accumulation in soil, which results in more negative water potential in plant system in general and leaves in specific (Flowers et al. 2010). Osmotic stress responsible for a number of physiological changes predominantly interruption/injury of membranes, nutrient imbalances, impaired ability to detoxify reactive oxygen species (ROS), differences in the antioxidant enzymes, and decrease in stomatal aperture in the initial stages finally leads to decreased photosynthetic activity (Kumar et al. 2016). Salinity stress is also considered as a hyper-ionic stress. One of the most detrimental effects of salinity stress is the accumulation of Na^+ and Cl^- ions in plant tissues.

Entry of both Na^+ and Cl^- into the cells causes severe ion imbalance and excess uptake causes significant physiological disorders. High Na^+ concentration inhibits

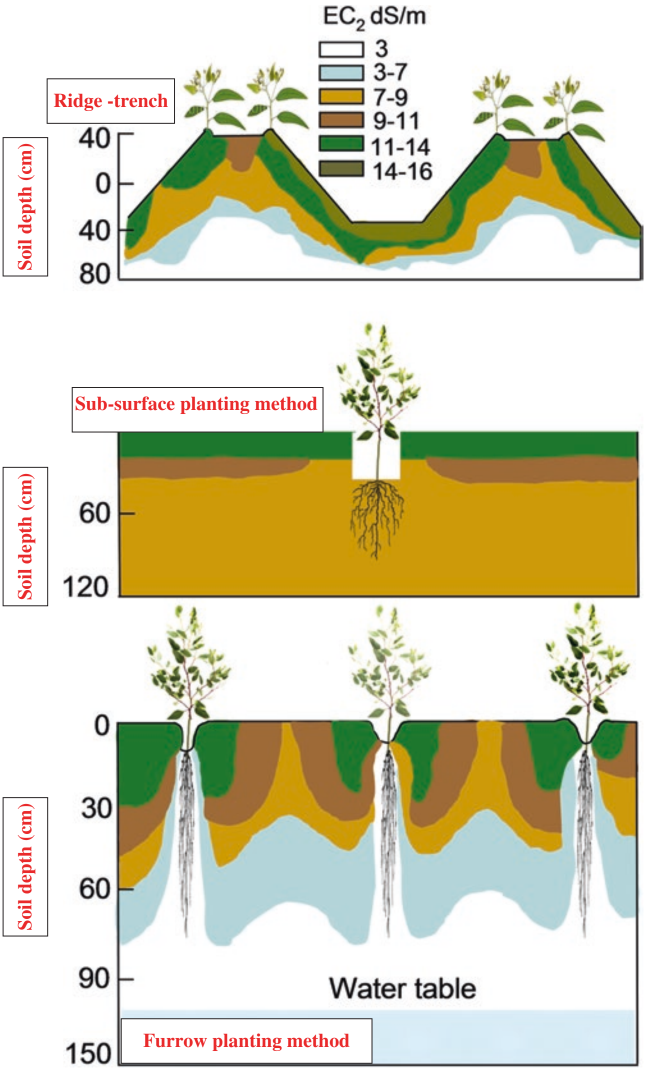

Fig. 16.7 Salt distribution pattern in ridge-trench, subsurface, and furrow planting methods in saline soils (Source: Dagar 2014)

uptake of K^+ ions which is an essential element for growth and development that results into lower productivity and may even lead to death (Munns 2005; Rahnama et al. 2010; James et al. 2011). In the last two decades, ample research has been done to understand the mechanism of salt-tolerance in model plant *Arabidopsis* (Zhang and Shi 2013). Genetic variations and differential responses to salinity stress in plants differing in stress-tolerance enable plant biologists to identify physiological mechanisms and sets of genes that are involved in increasing stress tolerance.

Ion homeostasis by ion uptake and compartmentalization is crucial for plant growth during salt-stress. Plants cannot tolerate high salt concentration in their cytoplasm. Therefore, the excess salt is either transported to the vacuole or sequestered in older tissues which eventually sacrificed for the protection of the plants from salinity-stress (Reddy et al. 1992; Zhu 2003).

Many plants showed an efficient mechanism to keep the ion concentration in the cytoplasm at low level. Membranes and their associated components play an integral role in maintaining ion concentration within the cytosol during the period of stress by regulating ion uptake and transport. The transport phenomenon is carried out by different carrier proteins, channel proteins, antiporters, and symporters. Maintaining cellular Na^+/K^+ homeostasis is pivotal for plant survival in saline environments. Plants maintain a high level of K^+, i.e., ~100 mM ideal for cytoplasmic enzyme activities (Munns 2005; Kumar et al. 2016). Within the vacuole, K^+ concentration ranges between 10 and 200 mM. The vacuole serves as the largest pool of K^+ within the plant cell. K^+ plays a major role in maintaining the turgor within the cell. It is transported into the plant cell against the concentration gradient via K^+ transporter and membrane channels. High-affinity K^+ uptake mechanisms are mediated by K^+ transporters when the extracellular K^+ concentration is low, whereas low-affinity uptake is carried out by K^+ channels when the extracellular K^+ concentration is high. Thus, uptake mechanism is primarily determined by the concentration of K^+ available in the soil. On the other hand, a very low concentration of Na^+ ion (about 1 mM or less) is maintained in the cytosol. During salinity stress, due to increased concentration of Na^+ in the soil, Na^+ ion competes with K^+ for the transporter as they both share the same transport mechanism, thereby decreasing the uptake of K^+ (Sairam and Tyagi 2004; Flowers et al. 2010). Elongation of stem and root was retarded by increasing salt-stress, but young roots and stem were most tolerant to salt-stress and were followed by leaves and old roots. However, production of young roots and death of old roots were found to be continuous, and plants apparently use this process as an avoidance mechanism to remove excess ions and delay onset of ion accumulation in the tissue, and this phenomena of "fine root turnover" is designated to the mechanisms of salt-tolerance (Ramoliya et al. 2004).

6.1 Soil Amelioration/Remediation Mechanism

The basic mechanism of salt-tolerance by the plants and crops is based on three processes like (1) salt exclusion, (2) salt excretion, and (3) salt accumulation (Fig. 16.8). The plants follow one of the three basic mechanisms to survive in saline soils besides the soil remediation benefit. Transpiration helps to reduce deposition of salt in the upper surface by absorbing soil moisture from the lower soil surface and thus keeping salt concentration high in the subsurface and low on surface soils. In addition, the deposition of salts in the upper layers of the soil is also minimized because of the shade of the trees which slows down the soil moisture evaporation rate and finally reduces the upward water flux containing salts through capillary

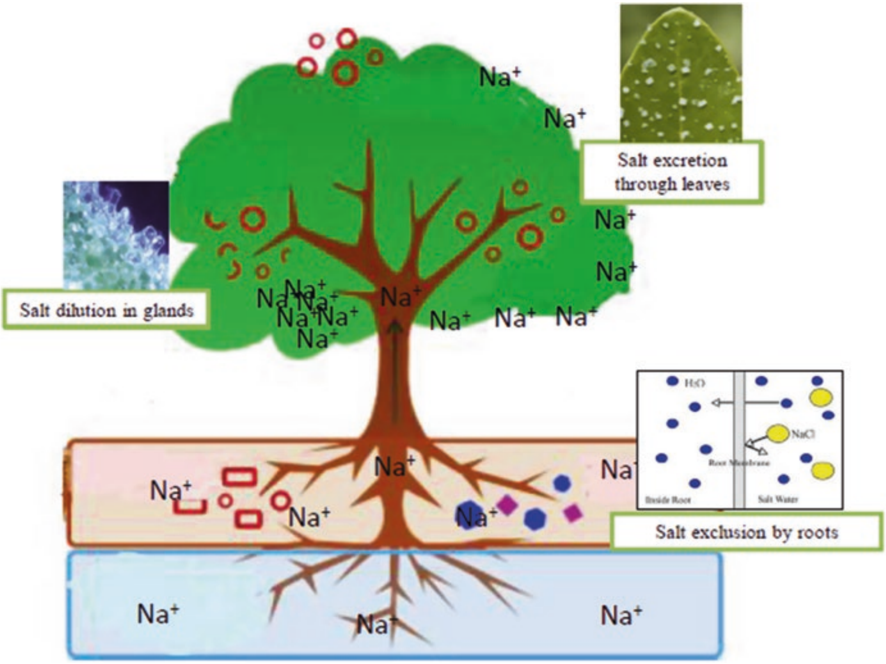

Fig. 16.8 Salt movement in soil and plant system in saline ecology

action to the soil surface. The deep-rooted trees also help in reducing the salinity problem. The deep and sturdy root system of a tree penetrates the soil and improves water permeability and facilitates the leaching of salts. Fine roots contribute significantly in the reclamation of soil structure, pH, and water permeability. Plant roots exude many compounds into the rhizosphere such as amino acids, sugars, phenolics, and organic acids which are responsible for salt neutralization in salt-affected soils. The organic acids from the decomposed leaf litter react with the calcium carbonate in the soil and release calcium which substitutes for sodium in the exchange complex. As the tree grows, a huge amount of litter is produced on the soil surface and releases several weak acids (humic and fumic) during decomposition process. These weak acids are responsible to lower down the pH and EC (electrical conductivity) of soils. The trees remove Na by the roots of trees acting as biodrain. The depletion of exchangeable Na in the soil is because of the biological production of carbonic acid (H_2CO_3) by tree roots and results in the solubilization of the native $CaCO_3$ present in such soils (Singh and Dagar 2005). Further, root system breaks the barrier of clay and loosens the subsoil and thus increases the permeability and downward translocation of sodium. This system also improved the physical properties of soil such as bulk density, porosity, soil moisture retention, and infiltration rate.

7 Agroforestry Systems for Saline Ecosystem

There are three basic approaches in practice to fight against salinization. These are (1) improving the drainage, (2) selection and breeding for salt-tolerance, and (3) alternate land uses. The alternate land use approach raises the possibility of using the vast stretch of saline soils for alternative production. Such approach can halt the further expansion in degradation besides augmenting the supply of food, forage, feed, timber wood, and above all ecosystem services. Agroforestry approaches come under the alternative strategies for rehabilitation of saline soils. Here, the possible agroforestry systems for productive utilization of saline ecologies are discussed in the light of their significance and cause and effect relationship.

7.1 Sequential Agroforestry System (Trees and/or Arable Crops)

Trees and arable crops can be grown in sequence instead of growing them simultaneously. This system is quite helpful in improving the fertility status of the soil. Nitrogen-fixing trees (NFTs) with fast-growing nature and short duration such as *Prosopis juliflora* with Kallar grass (*Leptochloa fusca*) can be grown for at least 4 to 5 years and then felled for fuel wood, fodder, or other small requirements of wood and their products. This system ameliorated the land to the extent that after harvesting trees, the land could be put under arable farming due to its improved and nutrient-enriched nature (Dagar et al. 2001; Singh et al. 2004; Singh and Dagar 2005; Dagar et al. 2016a, b). Rao and Gill (1990) raised *Sesbania sesban* initially for 4 years which ameliorated the soil and then cultivated rice-wheat cropping sequence. Only P and Zn were applied to the crops at recommended rates, and the response to applied N was separately determined in the plots fertilized with urea-N. The rice as the first crop yielded 6.4 Mg ha^{-1} in *Sesbania* plots without additional fertilizer application. Similarly, wheat yielded 2.2 Mg ha^{-1} in *Sesbania* plots compared to only 1.35 Mg ha^{-1} in the control plots. About 0.85 Mg ha^{-1} additional grains as well as 17 kg ha^{-1} of additional N ha^{-1} was derived from mineralization of organic residues. The total N uptake of crops in the control was 142 kg ha^{-1} and in *Sesbania* plots 222 kg ha^{-1}. The organic fertilization was 2.5 times effective than inorganic N fertilization.

7.2 Agri-silvicultural Systems (Trees + Arable Crops)

This system involves the conscious and deliberate use of land for the concurrent production of agricultural crops along with trees. Multipurpose trees (MPTs) are raised along with agricultural crops in the alley space. A series of experiments were conducted at CSSRI, Karnal, on reclaimed or normal soils to identify crops and crop sequences that can be grown in association with established plantations. But much was not done as far as saline soils are concerned. A good number of *Eucalyptus*-based systems with varying densities and under crops were developed for waterlogged saline soils (Dagar et al. 2016a, b). The Central Soil Salinity Research Institute, Karnal, Haryana (India) is in process to develop *Eucalyptus tereticornis* and *Melia composita*-based agri-silviculture system for saline ecologies. Low water-intensive crops like pearl millet and mustard have been taken as intercrops (*details given in case study section*).

7.3 Agri-horti System (Fruit Trees + Arable Crops)

Majority of fruit trees are sensitive to salinity but some of them can be grown on saline soils satisfactorily. This is based on the research work carried by various workers but especially Revender et al. (2004) and Dagar et al. (2008) who recommended that *Ziziphus mauritiana*, *Emblica officinalis*, *Carissa carandas*, *Aegle marmelos*, *Punica granatum*, *Syzygium cumini*, and *Tamarindus indica* could be grown in moderately saline soils. The research work carried out at ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, revealed that different fruit-based agroforestry systems have been developed and commonly practiced by the farming communities of the region. The systems comprised of Bael (*Aegle marmelos*), Aonla (*Emblica officinalis*), and Karonda (*Carrisa carandas*) as tree components, and cluster bean (in kharif) and barley (in rabi) as subsidiary components have been found practically and economically feasible with the moderate (ECiw 4–5.8 dS m^{-1})- to high-salinity (ECiw 8.2–10.5 dS m^{-1}) water (Dagar et al. 2008, 2016a, b). Saline soils under long-term tree cover exhibit overall improvement in soil quality which paves the way to increase in soil organic carbon, nitrogen contents, microbial biomass, and above all microclimate modification by uptake of roots from deeper soil layers (Sharma et al. 2014).

7.4 Silvopastoral System (Trees + Grasses)

The production of woody plants combined with pasture is referred as silvopastoral system. The trees and shrubs may be used primarily to produce fodder for livestock, or they may be grown for timber, fuel wood, and fruit or to ameliorate the saline soil. In waterlogged saline areas, several grasses such as *Leptochloa fusca* and species of *Aeluropus*, *Eragrostis*, *Sporobolus*, *Chloris*, *Panicum*, and *Brachiaria* can be successfully grown along with salt-tolerant trees for viable and sustainable silvopastoral systems to sustain livestock productivity (see Dagar 2014). *Aeluropus lagopoides*, *Sporobolus helvolus*, *Cynodon dactylon*, *Brachiaria ramosa*, *Paspalum* spp., *Echinochloa colonum*, *E. crus-galli*, *Dichanthium annulatum*, *Vetiveria*

Table 16.4 Promising grass species for silvopastoral system in saline soils

Range of tolerance (EC dS m^{-1})	Grass species
Highly tolerant (25–35)	*Cynodon dactylon* *Aeluropus lagopoides* *Sporobolus* spp. *Leptochloa fusca*
Tolerant (15–25)	*Dichanthium annulatum* *Saccharum spontaneum* *Chloris gayana* *Brachiaria mutica* *Cenchrus ciliaris* *Panicum* spp.
Moderately tolerant (10–15)	*Lasiurus sindicus* *Andropogon annulatus*

zizanioides, and *Eragrostis* sp. are important grasses which are tolerant to both salinity and stagnation of water and can successfully be grown in silvopastoral systems. Species of *Ziziphus*, *Atriplex*, *Kochia*, *Suaeda*, *Salsola*, *Haloxylon*, and *Salvadora* are prominent forage shrubs of saline regions and browsed by camel, sheep, and goat (Dagar 2014).

Most suited tree species for the system in saline soils are *Prosopis juliflora*, *Salvadora* spp., *Acacia nilotica*, *Pithecellobium dulce*, *Parkinsonia aculeata*, *Casuarina equisetifolia*, *Terminalia arjuna*, *Tamarix articulata*, and *Pongamia pinnata*. Similarly, the grass species such as *Leptochloa fusca*, *Chloris gayana*, *Brachiaria mutica*, and *Sporobolus* spp. are used on such soils (Table 16.4). *P. juliflora* (tree) and *L. fusca* (grass) were grown concomitantly which resulted in decrease of soil EC & pH and increase in soil nutrients namely organic carbon (%), available NPK at soil depths of 0–15 cm and 15–30 cm in six-year-old plantations. This system also improved the physical properties of soil such as bulk density, porosity, soil moisture, and infiltration rate over sole tree plantation.

Promising salinity-tolerant MPTs along with grasses, well adapted in the agroforestry systems and developed to reclaim such soils, are presented in Table 16.4.

7.5 Multipurpose Woodlots (Trees)

In this system, special location-specific MPTs are grown mixed or separately planted for various purposes such as wood, fodder, soil protection, soil amelioration, etc. Salinity-tolerant MPTs are raised in block plantation with close spacing. In addition to biomass production, trees help in amelioration by improving physical, chemical, and biological properties of saline soils.

7.6 *Saline Aquaforestry/Saline Aquaculture(Trees + Fish)*

Twin problems of salinity and waterlogging, as existing in many parts of southwestern Haryana and Punjab, have necessitated the development of alternative approaches to reclaim such landmasses. The degraded soil and water resources in these regions can be put to profit through shrimp and fish farming (Purushothaman et al. 2014). Inland saline aquaculture is a popular practice in saline tracts of Australia, Israel, and the USA (Allan et al. 2009). The ICAR-CSSRI, Karnal, Haryana (India) has worked out the feasibility of commercial fish farming in highly saline conditions at Nain Experimental Farm, Panipat, Haryana. Despite constraints such as high salinity of pond water (4–25 dS m^{-1} depending on season), low water availability, and high evaporative losses, fish growth was about 400–600 g in 6 months and 600–800 g in 1-year period (CSSRI 2013). On the peripheries of the pond, agroforestry trees can be grown to cater the bona fide needs of the farmer like fuel wood, small timber, fodder, and other tree-related tangible and above all environmental benefits. Eucalyptus can be successfully grown on the berms of the ponds and will be helpful in keeping the surface soil salinity under check. However, such combinations are not still investigated thoroughly, but such practices will be helpful in the economic sustenance of farms in the saline ecologies.

7.7 *Homestead/Multi-enterprise Agriculture Model*

The multi-enterprise model is developed in ICAR-CSSRI, Karnal, Haryana (India), for post-reclamation phase specifically suitable to small and marginal farm stakeholders. The model consists of diverse components like multiple combinations of horticultural species, MPTs, arable crops, vegetables, fishery, poultry, animal component, and beekeeping depending upon the land availability and financial inputs. The main outcome features of the developed system are sustainable resource use efficiency, regular income, and above all employment generation (Gajender et al. 2016; Sharma et al. 2016). Such models are standardized for highly saline black soils of Gujarat and coastal saline soils of West Bengal (Singh 2009a, b; Sharma and Chaudhari 2012).

7.8 *Energy Plantation*

There is a tremendous scope of biofuels (energy plantations) in the prevailing scenario of climate change. The production of woody biomass based on carbon neutral technology from areas not suitable for any traditional agriculture production would therefore be a unique opportunity. Biomass is an organic material which has stored solar energy from sunlight in plants through the process of photosynthesis. Unlike fossil fuels, biomass does not add carbon to the atmosphere as it absorbs the same amount of carbon dioxide while growing. Therefore, it is the cheapest, eco-friendly, and renewable source of energy. India, being a fast-growing economy with large import of crude oil, makes it more relevant in the present context. Fuel wood accounts for 20–30% of all energy needs in India and more than 90% of this is in the domestic sector. Therefore, fuel wood is more than just a commodity being consumed, supplied, processed, and traded. India needs 6–7% energy growth per year. Wood energy can be technically efficient, economically viable, and environmentally sustainable fuel option during the current energy deficit scenario. It is equally important to feed the fuel wood for domestic consumption with environmental and social benefits (Banyal 2013). In saline areas, salt-tolerant trees can be a potential alternative to conventional agriculture. Trees on saline wastelands produce timber for construction or for energy, i.e., charcoal for cooking or electricity production through gasifier techniques. Such landscape fashion also functions as windscreens, protects the soil against erosion, adds organic matter and nitrogen to soil, and above all sequesters carbon helping in mitigating climate change adversities.

8 Agroforestry Systems: Case Studies

8.1 Agroforestry Systems in Dryland Saline Ecologies

8.1.1 *Prosopis cineraria*-based Agroforestry for Hot Arid Regions of Gujarat and Rajasthan

Diversified production system is essential to cater to the multifarious demands of human beings as well as livestock population in the hot/dry arid regions. People not only plant this tree on their farmlands but also protect and take care of randomly growing tree or seedlings regenerated. Maintaining 833 trees per ha at the age of 2–3 years, 417 trees per ha at 4–6 years, 278 trees per ha at 6–7 years, and 208 trees per ha at 11 years or above age plantations is found to increase 10–15% crop yield as compared to sole crop growing without trees. In addition to crop yield, *P. cineraria* provides 350–1040 g pods per tree used as vegetable when raw and 0.85 Mg ha^{-1} $year^{-1}$ dry leaf fodder at 12 years of age with 208 trees per ha (Singh 2009a, b). More details are given by Soni et al. in the previous chapter of this publication.

8.1.2 *Salvadora persica*: Potential Tree for Agroforestry on Highly Saline Black Soils (Vertic Haplustept)

Salvadora persica is a potential species for the arid saline land restoration program. It provides fodder especially for camel, feed for birds, pharmaceutical derivatives, and seed oil for industrial purposes. It is considered as one of the best sources for sustaining livelihood of the populace. It is one of the dominant tree species of the

Table 16.5 Seed production and economic returns of *Salvadora persica* plantations in saline soils

Year(s)	Gross seed yield (Mg ha^{-1})	Planting cost (₹ha^{-1})	Fertilizer and harvesting cost (₹ha^{-1})	Returns (₹ha^{-1})		Cost/benefit ratio
				Gross	Net	
1st	Nil	2760	–	Nil	Nil	–
2nd	0.725	2760	500	3625	365	8.93
3rd	0.978	–	550	4890	4340	0.13
4th	1.580	–	650	7900	7250	0.09
5th	1.838	–	750	9190	8440	0.09

Source: Gururaja Rao et al. (2013)

Kutch region (northwest saline desert) of Gujarat state in India. It also grows successfully in coastal areas as well as in nonsaline and marginal semiarid central area of the Saurashtra region, south of the Kutch region. The tree species is found to be salt-tolerant at seed germination and seedling stages.

Attempts were made by CSSRI, Regional Station, Bharuch, Gujarat, to assess the growth, biomass production, and seed and oil yield as well as cost/benefit ratio of growing *Salvadora persica* on highly saline black soils with varying salinity in Gujarat state. A complete package and practice of agro-technology for raising of *Salvadora* sapling in saline water, field planting, and crop harvest was developed. The studies revealed that the sapling could be raised with saline water of ECiw 15 dS m^{-1}. The cost of raising 500 saplings worked out to be ₹455. The cost of field operations including raising of nursery was ₹2760 ha^{-1} in the first year. In subsequent years, the recurring costs would be mainly the labor for fertilizer application and harvesting. By the fifth year, the plants gave seeds at 1800 kg ha^{-1}, thus giving net returns to the tune of ₹8400 ha^{-1} (Table 16.5).

Thus, this species meets twin objectives, i.e., giving economic returns for the highly saline black soil and providing eco-restoration through environmental greening (Gururaja Rao et al. 2013). The decreasing trend in soil salinity both at the surface and subsurface layers (EC 6.1–8.0 dS m^{-1}) has been observed after 4 years of planting which may be attributed to high saline groundwater and its upward flux to the surface. Under lower salinity levels, the better root establishment and growth might have facilitated greater leaching of salts. *Salvadora persica* grown under highly saline conditions was also found to possess very low amounts of Na^+ and Cl^- in flower buds and berries. While the berries/seeds showed low content of Na^+ (270 μmoles g^{-1} dry weight) and Cl^- (242 μmoles g^{-1} dry weight), the bark, senescing leaves, and roots together showed very high amounts of Na^+ (32,790 μmoles g^{-1} dry weight) and Cl^- (34,370 μmoles g^{-1} dry weight). This can be ascribed to selective discrimination against Na^+ and Cl^- during phloem loading in source leaves, resulting in low levels of these ions accumulating in berries/seeds.

8.1.2.1 Economic Returns

The cost/benefit ratio was very high in the first year after planting due to high initial planting costs and low seed yield. The major input costs were confined only to harvesting and fertilizers from the second year onward which lead to low cost/benefit ratio. The cost/benefit ratio decreases with advancement of age and indicates that this apart from providing returns also adds to the environmental stability with ecological restoration of highly saline black soils in Gujarat. Another study indicated that *S. persica* can be cultivated as a source of industrial oil on both saline and alkali soils for economic and ecological benefits, otherwise not suitable for conventional arable farming (Reddy et al. 2008). Therefore, it was evident from several studies that *Salvadora persica* is a very promising species for saline soil where arable farming is not possible directly. *S. oleoides* has also similar properties and found more frequently in arid regions of Rajasthan.

8.2 Agroforestry System for Irrigated Saline Ecologies

The ICAR-CSSRI, Karnal, Haryana, India, has been actively involved in developing suitable agroforestry systems for irrigated saline ecologies. In a case study, *Eucalyptus tereticornis*- and *Melia composita*-based farm production agroforestry systems are being evaluated for saline conditions. Low water-intensive crops, namely, pearl millet in *kharif* and mustard in *rabi* seasons were grown as intercrops. Both the trees and inter-crops were given saline irrigation with varying salinity of ECiw from <1 dS m^{-1} (good-quality water) to 12.0 dS m^{-1}. The soil of the experimental site was saline with poor-quality of groundwater, and the soil ECe ranged from 4 to >30dS m^{-1}. The soil pH ranged from 7.21 to 9.25. The plantations of *Eucalyptus tereticornis* and *Melia composita* were done in line geometry with 4 m × 3 m and 6 m × 3 m spacing. Plantation was done in subsurface furrow irrigation method. *Eucalyptus* is a well-known agroforestry tree species with rice-wheat cropping system on reclaimed salt-affected soils (Ram et al. 2011; Kawasaki et al. 2010). But it is not tested with low water-intensive crops. *Melia composita* could be the potential plant due to its wider adaptability and multidimensional uses. Therefore, this is taken for the first time to test under salinity conditions to have *Melia*-based production models for saline soils.

The *Eucalyptus* and *Melia* trees showed good establishment (98%) and growth performance under saline conditions when resorted to saline irrigation in cyclic mode. However, the values of growth parameters showed decreasing trend with increase in salinity level in irrigation regimes. Pearl millet performed well with both the plantations (Fig. 16.9). The yield of pearl millet was higher (859 kg ha^{-1}) in the plots irrigated with good-quality available water (ECiw <1 dS m^{-1}) and found to show decreasing trend with the increase in salinity level in irrigation water in *Eucalyptus* plantations up to ECiw 12 dS m^{-1}. The lowest yield (541 kg ha^{-1}) was obtained in the plots irrigated with higher salinity (ECiw 12 dS m^{-1}) water. The pearl millet yield was higher (641 kg ha^{-1}) in BC (below crop) than AC (away crop)

Fig. 16.9 Pearl millet crop with *Eucalyptus tereticornis* (left) and *Melia composita* plantations (right)

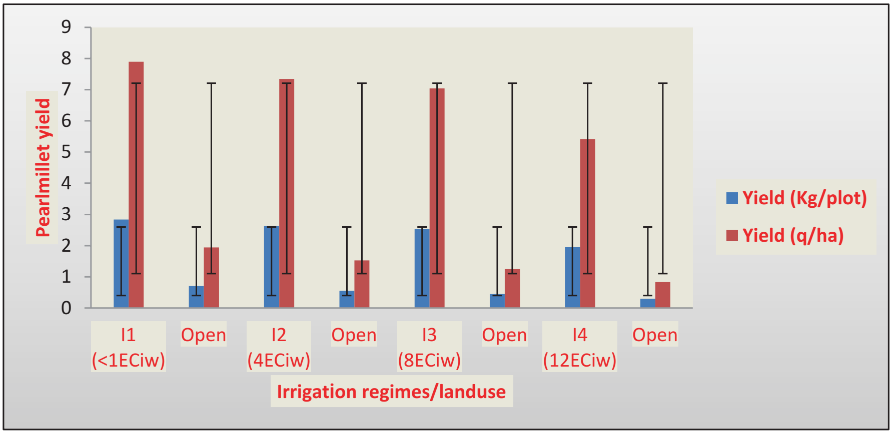

Fig. 16.10 Effect of saline irrigation regimes and land use pattern on pearl millet yield in *Melia*-based agroforestry system in saline soils (yield $q = 100$ kg)

(480 kg ha^{-1}) under *Eucalyptus*-based systems. The highest yield (789 kg ha^{-1}) was observed in the plots irrigated with good-quality available water (ECiw <1 dS m^{-1}) and the lowest (541 kg ha^{-1}) was with higher salinity (Fig. 16.10). The values of EC_2 and pH showed consistent increasing trend from lower (ECiw <1 dS m^{-1}) to higher (ECiw 12 dS m^{-1}) salinity levels. EC_2 and pH of soil were lower than the initial status in the plots irrigated with good-quality water, and there was a buildup of salinity toward higher level of salinity. Tree + crop gave low values of EC_2 and pH from initial status followed by sole crop and sole tree. The mustard yield showed similar trends as it was maximum (1338 kg ha^{-1}) in low salinity and minimum (704 kg ha^{-1}) in higher salinity in *rabi* season with *Melia* plantations (Fig. 16.11). The yield difference between treatment combinations of tree + crop and sole crop lowered down with the increase in the salinity level of irrigation water in both seasons. The higher intercrop yield under plantations may be ascribed to the synergistic

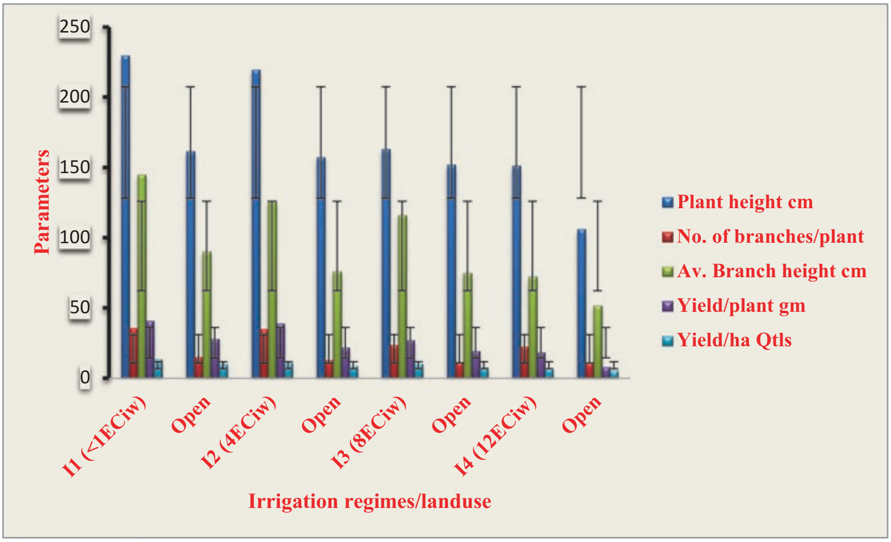

Fig. 16.11 Effect of saline irrigation regimes and land use pattern on mustard yield in *Melia*-based agroforestry system in saline soils (yield 1qtl =100 kg)

effect of trees with crops. Soil salinity was determined in terms of electrical conductivity and pH values at the time of sowing and harvesting of intercrops and gave invariable response to the irrigation regimes. The soil conditions improved in plots irrigated with low saline water and vice versa, and there was salt buildup in both seasons. It was found that pH and EC_2 values of the plots with crops were lesser than fallow plots while compared with the initial soil status.

The irrigation with best available water (ECiw ~1 dS m^{-1}) having tree + crop was found to be the best treatment to have better establishment and growth of trees and higher yield of under crops with positive remediation effect on soil in both the developed farming systems. The establishment of both tree species especially *Melia composita* on such ecologies is the uniqueness of the developed agroforestry systems from others. The findings are only based on the initial trends and may differ with the passing time as trees get older. But it is definite that the synergistic effect of trees and intercrops certainly makes saline soils of service use which results in the economic and ecological security of the farming communities (Banyal et al. 2017).

A long-term field study was conducted to assess the performance of forest tree species on calcareous soil of semiarid region in northwest India during 1991–1992 to 2010–2011. Tree saplings were planted at the sill of furrows and irrigated with saline water (EC 9.3 dS m^{-1}) regularly for the initial 3 years and thereafter only once for the next 5 years. Survival, growth, biomass production, water use and water-use-efficiency of tree species, and changes in some soil properties were monitored. *Tamarix articulata*, *Acacia nilotica*, *A. tortilis*, *Prosopis juliflora*, *Eucalyptus tereti-*

Fig. 16.12 Cluster bean with fruit tree *Emblica officinalis* (left) and *Aegle marmelos* (right) established with saline water (Source: CSSRI, cited by Dagar 2014)

cornis, *Azadirachta indica*, and *Cassia siamea* produced higher biomass and proved to be the preferred choice among the tree species. *Acacia tortilis* (hybrid), *Ziziphus mauritiana*, *Pithecellobium dulce*, *Melia azedarach*, *Cassia fistula*, *C. javanica*, *Callistemon lanceolatus*, and *Acacia farnesiana* showed moderate performance, while tree species like *Acacia auriculiformis*, *Albizia lebbeck*, *Bauhinia variegata*, *Cassia glauca*, *Syzygium cumini*, *Crescentia alata*, *Samanea saman*, and *Terminalia arjuna* were sensitive to dryland saline irrigation (Tomar et al. 2003; Dagar et al. in press). Water use of plantations did not vary among species, but water-use-efficiency differed markedly, with the highest biomass of 42.79 Mg ha^{-1} in *Tamarix articulata*. The soil organic carbon in the upper 0.3 m layer increased to ~5.0 g kg^{-1}, while $CaCO_3$ and exchangeable sodium percentage (ESP) decreased under the promising tree species. Thus, growing above recommended tree species using available saline groundwater would not only help in productive rehabilitation of abandoned calcareous soils of arid regions but also ensure carbon sequestration, improvement in environment, and long-term ecological security on such lands.

Among fruit trees, *Feronia limonia*, *Ziziphus mauritiana*, *Carissa carandas*, *Emblica officinalis*, and *Aegle marmelos* could be established irrigating with saline water up to EC 10 dS m^{-1}, and intercrops in wider spaces between rows (5 m) such as cluster bean (Fig. 16.12), mustard, and barley could be raised with success (Table 16.6) applying one or two irrigations (Dagar et al. 2016a, b). This appears a very viable agroforestry system for such soils.

Grasses such as *Panicum maximum*, *P. coloratum*, *P. antidotale*, *P. laevifolium*, *P. virgatum*, *Brachiaria mutica*, *Cenchrus ciliaris*, and *C. setigerus* could successfully be grown with saline irrigation up to ECiw 10 dS m^{-1}. These along with trees mentioned above may form productive silvopastoral system in dry regions. Many medicinal plants such as *Plantago ovata*, *Withania somnifera*, *Ocimum sanctum*, *Catharanthus roseus*, *Achyranthes aspera*, *Lepidium sativum*, *Aegle marmelos*, and *Cassia angustifolia* and aromatic grasses such as *Vetiveria zizanioides*, and *Cymbopogon flexuosus* could be cultivated with success as crop in isolation and as intercrops with forest and fruit trees. Flowers such as *Chrysanthemum indicum*, *Matricaria chamomilla*, *Calendula*, etc. have been successfully evaluated with saline water at the same site (Fig. 16.13).

Table 16.6 Grain and straw (in paranthesis) yield (Mg ha^{-1}) of intercrops grown with fruit trees

Fruit trees	Treatment	Average of 5 years (2003–2007)		Average of 4 years (2008–2011)	
		Barley	Cluster bean[a]	Mustard	Cluster bean[b]
	Control	3.55 ± 0.31 (3.82 ± 0.23)	1.41 ± 0.27 (2.22 ± 0.36)	1.58 ± 0.14 (3.16 ± 0.29)	0.96 ± 0.15 (1.55 ± 0.19)
Cc	Low	3.43 ± 0.34 (3.75 ± 0.29)	1.36 ± 0.27 (2.10 ± 0.32)	1.41 ± 0.09 (2.88 ± 0.16)	0.77 ± 0.02 (1.35 ± 0.06)
	Low/high	3.32 ± 0.33 (3.63 ± 0.18)	1.28 ± 0.28 (1.93 ± 0.30)	1.33 ± 0.07 (2.76 ± 0.13)	0.71 ± 0.02 (1.30 ± 0.04)
	High	2.99 ± 0.25 (3.26 ± 0.15)	1.21 ± 0.28 (1.90 ± 0.35)	1.18 ± 0.08 (2.61 ± 0.10)	0.69 ± 0.02 (1.26 ± 0.02)
Eo	Low	3.56 ± 0.34 (3.89 ± 0.25)	1.38 ± 0.29 (2.27 ± 0.42)	1.73 ± 0.08 (3.61 ± 0.17)	0.83 ± 0.08 (1.43 ± 0.13)
	Low/high	3.29 ± 0.28 (3.42 ± 0.26)	1.27 ± 0.26 (2.09 ± 0.35)	1.66 ± 0.07 (3.48 ± 0.12)	0.78 ± 0.07 (1.39 ± 0.13)
	High	3.04 ± 0.22 (3.16 ± 0.22)	1.16 ± 0.26 (1.87 ± 0.30)	1.58 ± 0.06 (3.36 ± 0.10)	0.73 ± 0.06 (1.33 ± 0.11)
Am	Low	3.27 ± 0.31 (3.50 ± 0.22)	1.30 ± 0.29 (2.14 ± 0.38)	1.26 ± 0.07 (2.68 ± 0.12)	0.78 ± 0.13 (1.41 ± 0.22)
	Low/high	3.08 ± 0.30 (3.30 ± 0.24)	1.25 ± 0.27 (1.99 ± 0.33)	1.21 ± 0.08 (2.55 ± 0.15)	0.72 ± 0.12 (1.34 ± 0.21)
	High	2.78 ± 0.24 (2.99 ± 0.19)	1.14 ± 0.25 (1.79 ± 0.28)	1.11 ± 0.07 (2.33 ± 0.08)	0.66 ± 0.14 (1.26 ± 0.24)

Source: Dagar et al. (2016a, b)
Deviation from mean (±) is between the mean yields of the years
Cc *Carissa carandas*, Eo *Emblica officinalis*, Am *Aegle marmelos*, Control = Intercrop raised with low saline water without plantations
[a] Average of 4 years
[b] Average of 3 years

8.3 *Agroforestry Systems for Inland Waterlogged Saline Ecologies*

Introduction of canal irrigation in dry regions without provision of drainage causes rise in ground table leading to waterlogging and salinity. For lowering down water table, conventional drainage is the best option, but that is a costly proposition and has environmental consequences. Recently, biodrainage options have been found successful. Trees such as *Eucalyptus tereticornis* planted in blocks or on boundaries of cultivated fields have shown a promise (Fig. 16.14). Ram et al. (2011) have shown that the system is effective and socially accepted by the farming community.

Further, Dagar et al. (2016a, b) studied the impacts of agroforestry system comprising of wheat and rice crops in combination with *Eucalyptus tereticornis* trees for remediation of waterlogged saline soils. In one experiment, three spacings, viz., 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m, were evaluated with respect to growth, biomass, and transpiration potential. Block plantations of *Eucalyptus* generated 141.7 Mg ha^{-1} timber wood biomass and sequestered 66.5 Mg C ha^{-1}. The transpi-

Fig. 16.13 Evaluation of annual flowers using saline water up to ECiw 10 dS m^{-1} in dry conditions (forest trees in the background) (Source: CSSRI)

Fig. 16.14 *Eucalyptus tereticornis* on field boundary (wheat) in waterlogged areas of Haryana, India (Photograph courtesy JC Dagar)

ration rate of *Eucalyptus* in block plantation on an average was 40.0 L day^{-1} $tree^{-1}$ as compared to 68.0, 71.5, and 73.8 L day^{-1} $tree^{-1}$ in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m tree spacing, respectively, in strip plantation. The corresponding total amount of water transpired per annum was 1825 mm in block plantation and 745, 391, and 269 mm in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m tree spacings. Due to high transpiration rate of *Eucalyptus*, water table was lowered by 43.0 cm in 1 m × 1 m, 38.5 cm in 1 m × 2 m, and 31.5 cm in 1 m × 3 m spacings, respectively, during the fourth year of plantation than in adjacent fields without plantation. Near the tree lines, grain yields of both wheat and rice were comparatively low. But lowering of water table resulted in improvement in soil properties which produced 1.7 and 1.3 times higher grain yield of wheat and rice, respectively, compared to control. The results suggested that in a rotation of 6 years, 1 m × 1 m spacing for strip plantation of *Eucalyptus* in paired rows on farm acre line was the optimum for achieving higher water table draw down, wood biomass production, carbon sequestration, and crop productivity on waterlogged fields.

8.4 Agroforestry Systems for Coastal Regions

There is increasing trends in salinity of low-lying coastal areas due to sea level rise which found to severely affect the productivity of agricultural land. Agroforestry practices are quite helpful to reduce the salinity level along the coastal areas. Many technologies have been developed to sustain crop production in coastal saline soils of the country. "Dorovu" technology to skim fresh water floating on the saline water has gained immense popularity in many coastal regions. Other such technologies include *rabi* cropping in mono-cropped coastal saline soils, rainwater harvesting in dugout ponds, salt-tolerant rice varieties (*Sumati* and *Bhootnath*), efficient nutrient management, and integrated rice-fish culture (Sharma and Chaudhary 2012).

The coastal saline soils brought under cultivation by constructing protective embankments to prevent inundation by seawater. The protective embankments have a side slope of 3:1 on the sea or riverside and 2:1 on the country or landside with about 1 m tree broad above the highest tide level. Hence, the height of embankment depends on the highest tide level of the year. A suitable shelter with trees or grasses is required to protect the embankments from tidal wave action. *Casuarina*- and *Eucalyptus*-based agroforestry systems are common in sandy soils having saline underground water. Multitier agroforestry systems such as homegardens were reported to resist the climate change impacts. It is well documented that homegardens and mangroves were found efficient to protect the coastal areas from the 2004 *tsunami*. Mattsson et al. (2009) documented the success story about the protection of area with homegardens in Hambantota district, Sri Lanka. They found that houses with homegardens or near neighbors' homegardens received less damage than those without homegardens during the *tsunami* period. Communities in the coastal region

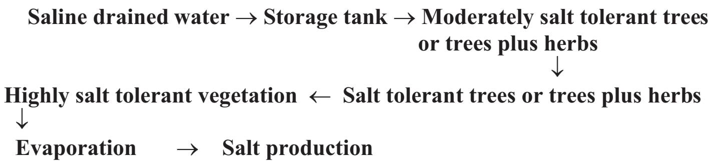

Fig. 16.15 Schematic diagram for reuse of drainage water for saline agriculture

are highly vulnerable to climate change vagaries. They have high rates of poverty and villagers depend on natural resources such as forestry and fishery stocks for their livelihoods. In this context, Bangladesh is implementing a community approach to climate change adaptation through afforestation. The FFF model of forest, fish and fruit is the innovative coastal agroforestry. This system offers diversified livelihood options with reduced salinity (Shah 2014). For more details, see Dagar et al. (2014).

For coastal regions, Samphire (*Salicornia bigelovii*) is a very important salt bush, which yields about 28.2% seed oil, 31.2% protein, 5.3% fiber, and 5.5% ash from seeds. The oil resembles to Saffola oil and is considered for cosmetic and pharmaceutical industries. Straw and cake are used as forage and considered suitable for paper pulp. It can be irrigated with water of sea salinity. The plant is experimented at Luni in Kachchh (Gujarat) and Bhavnagar in Pali (Rajasthan). No doubt subsurface drainage helps in leaching down the salts from the root zone, but it is a highly costly option and has environmental limitations. Biodrainage on the other hand is environmental friendly and a cheap technique which can be adopted at least as a preventive measure.

A schematic model for utilization of the drainage effluents has been shown in Fig. 16.15:

8.4.1 Agroforestry in Coastal Saline Soils of Bangladesh (Case Study)

The study conducted by Wicke et al. (2013) examined an agroforestry system based on combination of most common agricultural land use and reforestation in the coastal area affected by soil salinity due to intrusion of seawater. Local rice variety was transplanted during the monsoon and harvested in November and December. The rice fields were intersected by tree lines. Assuming a square field of 1 ha, there were two lines where each line has two rows of trees and each row accounted for 50 trees with tree spacing of 2 m × 2 m. The tree density was 200 trees per hectare and the tree lines covered 8% of the land. This practice is commonly followed and *Eucalyptus camaldulensis* is a common species in coastal Bangladesh. Two rotations of 10 years are considered and tree coppice after the first rotation, providing almost similar biomass as in the first rotation. In the economic performance analysis, *Acacia nilotica* has been assessed as an alternative tree species to *Eucalyptus camaldulensis*. The green house gas (GHG) balance for biomass production is constructed based on emissions from all activities related to biomass production. The GHG balance is expressed in terms of g CO_2eq MJ^{-1} and is translated into the amount of carbon sequestration per hectare over the lifetime of each plantation (Mg CO_2eq ha^{-1}) to provide an estimate of carbon sequestration potential of these systems. This is done by multiplying the GHG balance with biomass yield, energy content, and lifetime of plantation. Carbon credits from biosaline agroforestry are determined based on the GHG balance and carbon market trends. *Eucalyptus camaldulensis* yielded a biomass of 4.1 Mg ha^{-1} $year^{-1}$ at moderately saline sites (6 dS m^{-1}) to 0.9 Mg ha^{-1} $year^{-1}$ at extremely saline sites (25 dS m^{-1}), whereas, *Acacia nilotica* yielded 2.9 Mg ha^{-1} $year^{-1}$ at moderately saline soils and 1.8 Mg ha^{-1} $year^{-1}$ at extremely saline sites. The GHG balance of biomass production from biosaline agroforestry in the coastal saline soils of Bangladesh indicates that this system sequesters carbon at slightly to highly saline soils because of increased carbon stocks in belowground biomass, litter, and the soil. The NPV of the agroforestry systems is economically beneficial for local farmers, but the size of NPV depends strongly on the severity of soil salinity and tree species cultivated. Only on moderately saline lands, NPV of the *E. camaldulensis* production is higher than *A. nilotica*. In highly saline areas, the NPV is higher for *A. nilotica*. The economic value of the carbon sequestration for *E. camaldulensis* at moderately saline soils ranges between 0.01 and 0.15 k€ ha^{-1} depending on the carbon credit price.

9 Agroforestry System Evaluation

9.1 Biometric Approaches for Biomass Production

The allometric equations developed for normal soils are used for the trees growing on saline soils and certainly not the true representative of the estimates. The growth of the trees and crops in saline soils is entirely different as compared to the normal soils. So, it is the need of the hour to develop allometric approaches exacting to trees adapted to the saline soils. ICAR-CSSRI is in the process of developing biometric equations of *Eucalyptus tereticornis*, *Melia composita*, *Terminalia arjuna*, *Azadirachta indica*, and *Dalbergia sissoo* under field conditions on saline environment (CSSRI 2014). The previous studies carried out by the institute envisaged to develop the biosaline agroforestry systems for saline environments wherein ten species, namely, *Prosopis alba* (0465), *Prosopis alba*, *Prosopis juliflora*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Tamarix articulata*, *Pongamia pinnata*, *Jatropha curcas*, *Terminalia arjuna*, and *Cassia siamea*, were evaluated with reference to growth and biomass attributes under varying salinity regimes. Six-month-old uniform seedlings were planted in porcelain pots filled with washed coarse river sand. Five levels (0.40, 7.5, 12.0, 15.5, and 19.0 dS m^{-1}) of salinity treatments were tested during the first year and subsequently stepped up to 42 dS m^{-1} in the second year. Four replicates per treatment were harvested, washed, and sampled after 14 months of salinity treatment and the remaining after 2 years of salinization and separated into roots, stem, and leaves and processed for chemical analysis. Data on shoot

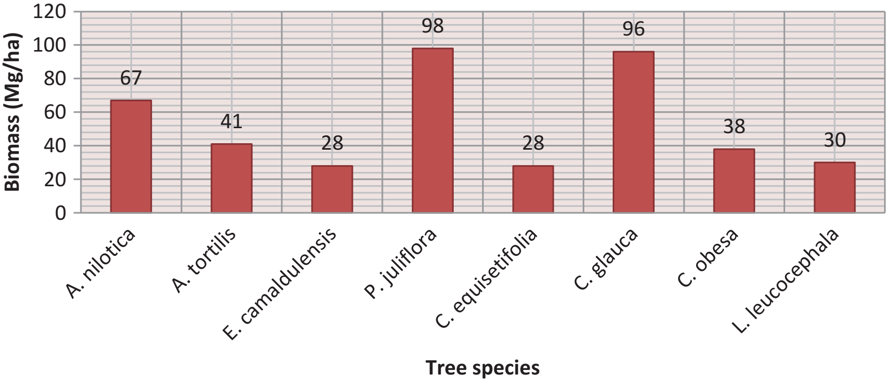

Fig. 16.16 Biomass (Mg ha^{-1}) of trees grown in saline soils at Sampla, Haryana (India) (Source: Tomar et al. 1998)

biomass (stem, branches, and leaves) and total plant biomass (all plant parts, i.e., roots, stem, branches, and leaves) were used to develop salinity response curves for selected tree species. At harvest, biomass of root, shoot, and leaf components were recorded for fresh and dry weight. Subsequently soil and irrigation/drainage water were also analyzed for maintaining salinity levels. Salinity curves were prepared for all the test species based on USDA "salt" model for determining "C" Cso and Co values. Locally available tested tree species, namely, *Eucalyptus tereticornis*, *Prosopis juliflora*, *P. alba*, *P. glandulosa*, *Acacia nilotica*, *Terminalia arjuna*, *Tamarix articulata*, *Pongamia pinnata*, *Jatropha curcas*, and *Cassia siamea*, showed higher tolerance and biomass than exotic germplasm such as *Acacia salicina*, *A. ampliceps*, and *Casuarina glauca*. Mechanisms of tolerance and growth were studied and salt-tolerance curves were developed. *Acacia*, *Casuarina*, *Eucalyptus*, *Prosopis*, and *Tamarix* species/accessions occupy the top positions among salt-tolerant tree species and provide higher biomass (CSSRI 2010). A study was conducted in saline soils to assess biomass production under field conditions at Sampla, Haryana (India), where plantation was raised through subsurface planting and irrigated initially with saline water in furrows. The initial ECe of soil ranged from 20 to 36 dS m^{-1}. The plantations were raised in 4 m × 4 m spacing. *Prosopis juliflora* was observed to be the most successful species yielding the highest biomass (98 Mg ha^{-1}) followed by *Casuarina glauca* (96 Mg ha^{-1}) and *Acacia nilotica* (67 Mg ha^{-1}) of 9-year-old plantations (Tomar et al. 1998; Fig. 16.16).

9.2 Soil/Environmental Quality Evaluation

Trees and agroforestry systems are the most suitable farming systems to cope with the negative impact of extreme weather events vis-a-vis climate change. The role of agroforestry in protecting the environment and providing number of ecosystem services is promoted as a key benefit of integrating trees into farming systems. The impact of agroforestry on the environment occurs at a range of spatial and temporal scales from fine-scale impacts on soil structure and quality to impacts on the society at regional or global scales. Most of the studies related to biosaline agroforestry have focused on ameliorative effects of trees on soil salinity and soil organic carbon content with respect to the environmental performance of the tree-based land use systems. However, very few studies have been executed to analyze environmental impacts accrued from agroforestry systems especially in saline environment. The greenhouse gas (GHG) balance of such systems has not been assessed despite their potential to sequester carbon through revegetating degraded sites and potential economic benefits from carbon credits.

9.3 Socioeconomic

There are several difficulties associated with the adoption of biodrainage, but it has potential for social acceptance among farming communities because of its edge to make waterloggedsaline soils of service use with low inputs. A preliminary survey was conducted in Haryana to assess the willingness of farmers for the biodrainage technology in which 99% farmers have shown their willingness for adoption of the technology (Ram et al. 2011; NAAS 2015). Still there is ample need to go for systematic socioeconomic impact analysis studies. But the basic data of such studies are lacking.

10 Methodological Challenges in Agroforestry Impact Evaluations

It is quite common to most of the land uses that there are methodological bottlenecks related to evaluation of the outcomes. The situation is of higher magnitude when we talk of agroforestry systems because of their complex nature. Nair and Dagar (1991) suggested some measures for evaluation of agroforestry systems. They emphasized that in order to improve the efficiency of indigenous systems and available modern technologies, it is essential to evaluate the existing agroforestry systems. Since productivity, sustainability, and social acceptability are the key attributes of all agroforestry systems, evaluation procedure should encompass all these attributes. The methods and procedures used in agroforestry vary at large. The available datasets are mostly inconsistent and often incomparable and inconclusive. Nair (2011) highlighted some of the common problems in existing methods and procedures for evaluations of outcomes in agroforestry systems (Table 16.7).

Table 16.7 Methodological problems in agroforestry system evaluations

S. no.	Common problems	Details
1.	Allometric equations	Aboveground biomass is estimated through allometric equations in agroforestry systems. This leads to the broad generalization and inaccuracy. This is due to non-availability of the true to type allometric equations exacting to tree species and agroclimatic zones. The situation is more worrisome about the saline soils. Here, the allometric equations developed for normal soils are used and certainly not the true representative of the estimate. The growth of the trees and crops is entirely different as compared to the normal soils. So, this is important to develop allometric models exacting to trees adapted to the saline soils
2.	Soil sampling	Soil sampling studies only limited to surface and/or subsurface soils. Sampling beyond the surface soil is important in case of tree-based land use systems because tree roots extend to deeper soil horizon. The role of sub-soils is highly important in long-term nutrient dynamics and C stabilization
3.	Pseudo-replication	It is common in agroforestry research to use pre-existing field plots of the same contiguous experimental units without true replicates of treatments. Statistical comparison between treatments of such studies may be invalid. But, this is not questionable in the statistical sense. In this situation, the treatment replicates extended over large tracts of land are considered as pseudo-replicates (Tonucci et al. 2011) whereas pots arranged in blocks in a greenhouse experiment are considered as replicates (Lopez-Diaz et al. 2011). Pseudo-replication problem can be removed through spatial interspersion of replication under systematic design. Composite samples drawn from large experimental units as replicates are used in forestry research. The land use systems kept here as fixed effect treatments. The results can't be used to make conclusions about agroforestry systems in true statistical sense because fixed effect model only restricted to the treatments in the study
4.	Repeated measurements	The fixed effect model applies to the repeated measures which refer to measurements made in time or space on the same subject or experimental unit. For example, in agroforestry experiment, we may have to draw soil samples from depth increments from the same sites or transects at defined horizontal distances from trees. When time and space are considered as treatments, they can't be randomly assigned to the depth/distance increments which otherwise treated as repeated measures rather than independent measurements (Howlett et al. 2011). The non-randomized nature of repeated measures designs often results in the violation of the assumptions necessary for valid univariate analysis. However, statistical procedures are available to address the limitations imposed by the model. In the case of soil depths at the same site, they could be stratified and each soil depth considered independently treating each site as a replication
5.	Chrono-sequence studies	Studies that are carried out to understand the change in soil carbon, and nutrients are often based on the assumption that the changes in carbon and nutrient stocks are likely to be linear with time. This may not be necessarily true in real sense. Even, it is difficult to know the residence of carbon that is sequestered initially in a system differs from that of later sequestered carbon. There are numerous such challenges which need to be addressed for realistic impact assessment studies in agroforestry landscapes

11 Agroforestry: Past and Future Headway

The start of organized research in agroforestry in early 1970s has taken different dimensions. Earlier, agroforestry was considered to provide bona fide needs of the communities by incorporating trees, crops, and animal component in unit land through varying interfaces. The main emphasis was on tangible outputs like biomass from trees and crop yield. But the current understanding of agroforestry systems is changed, and now agroforestry is considered a problem-solving science (Dagar and Tewari 2016). It is considered as a better climate change mitigation option than ocean and other terrestrial ecosystems because agroforestry provides ecosystem services such as carbon sequestration, biodiversity conservation, water quality enhancement, and land restoration. It was included in global program such as Reduced Emission from the Forest Degradation and Deforestation (REDD$^+$) related to climate change mitigation and adaptation. It is envisaged from the latest literature on agroforestry that this is beyond any doubt that agroforestry must play a definite role in answering the future global challenges. Now, there is a plethora of active markets of ecosystem services obtained from the developed agroforestry systems. However, lack of predictive metrics and the regulatory environment mechanisms are impeding the adoption of several ecosystem services. The major issues of maintaining food and fiber production, soil degradation (salinization), biodiversity decline, and climate change mitigation can be managed at a meaningful scale with sustenance through agroforestry option. Industrial agroforestry involved short- rotation forestry to accommodate agricultural crops in fast-growing plantations. The impact of agroforestry on the environment occurs at a range of spatial and temporal scales from fine-scale impacts on soil structure and quality to impacts on the society at regional and global scales. Future CO_2 mitigation initiatives will greatly benefit from incorporation of biodiversity component into the design, implementation, and regulatory framework. This will also bring the two quite different entities of biodiversity conservation and carbon sequestration together. The convergence of carbon sequestration with biodiversity conservation and salinity management presents a unique opportunity to tackle environmental problems together. Using an agroforestry approach will allow the integration of trees into farmland and not displace food production but rather stabilize agricultural systems and alleviate dryland salinity.

The path of agroforestry development as subject is divided into three scenarios (Fig. 16.17) based on existing and future use scales.

In scenario I, the emphasis was on production potential to have more biomass output. But with advancement of the subject and peoples' requirement, more stress was diverted to conservation issues like carbon and biodiversity in addition to existing outputs as in scenario I. The visible impacts of climate change forced the thinking in agroforestry toward ecosystem services as a whole to find out the solutions for the upcoming problems at the behest of climate change. The integration of variable parameters in agroforestry puts its strong stake in the times to come to provide solution to many of them. But with the beneficial effects, there is a major concern to

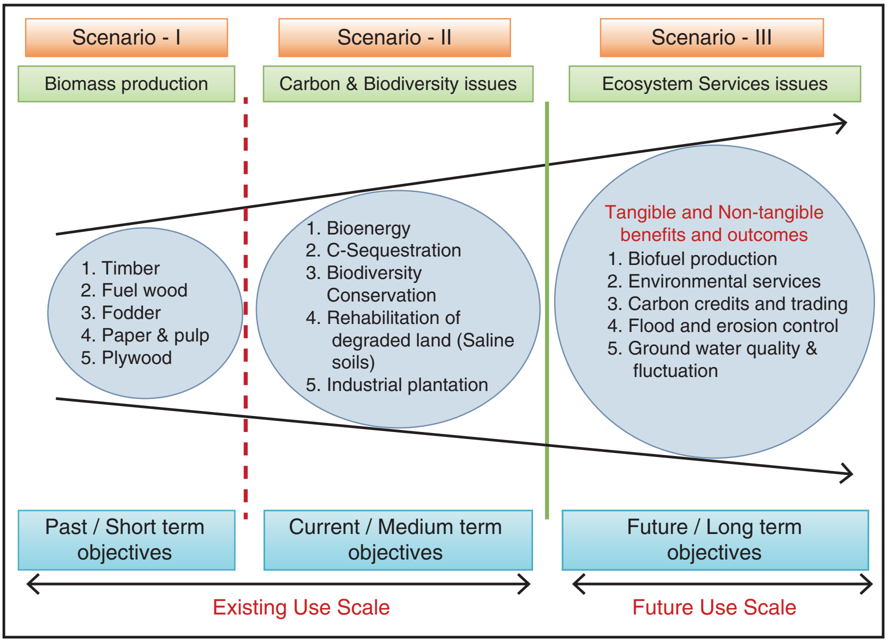

Fig. 16.17 Sequential journey of agroforestry as subject

devise methodology for its complete evaluation as complete ecosystem including the ecological services rendered by agroforestry systems. Therefore, it remains the millionaire question for researchers to give complete evaluation package of such versatile land use systems.

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Chapter 17
Prospects of Agroforestry for the Marginal Environments: Evidences from the United Arab Emirates

Asad Sarwar Qureshi and Shoaib Ismail

Abstract Dryland salinity and occurrence of highly saline groundwater are recognized as the major bottlenecks for the agricultural development in the marginal desert environment. In the United Arab Emirates (UAE), about 34% area is affected by salinity. The coastal sabkha areas are highly salinized (28.8 dSm^{-1}), whereas in the coastal region of the Abu Dhabi Emirate, salinity is more than 200 dS m^{-1}. The major causes of land degradation include use of brackish groundwater for irrigation, insufficient leaching of salts and upward movement of saline groundwater in the very hot environments. Rising sea levels along with the over-exploitation of fresh water resources also causes seawater intrusion in coastal zones. In the hyperarid environment of UAE, integrating trees and shrubs with other farm enterprises could be a useful strategy to increase system's productivity. Field studies conducted on UAE soils have shown that *Acacia ampliceps* can fix nitrogen under different salinity levels ranging from 10 dS m^{-1} to 30 dS m^{-1}, thus supporting the nutrient requirements for the two grasses, i.e. *Sporobolus arabicus* and *Paspalum vaginatum*. The average yield of these grasses varied from 22 to 28 Mg dry matter ha^{-1} $year^{-1}$. In addition, the foliage from the trees harvested at 2 m from the ground surface additionally provided ~10 Mg dry matter ha^{-1} $year^{-1}$. The *A. ampliceps* trees showed nodulation even at 30 dS m^{-1} with the bacteria showing the characteristic feature of gram-negative *Rhizobium*. The fixation of nitrogen by the *Acacia* trees helps in increasing the soil nitrogen through the root system and supporting the forages. In the (sabkha) coastal areas, establishment of halophytic plants such as *Atriplex* species can be advantageous due to low annual maintenance costs and their ability to survive high salt contents in the soil. As conditions become less severe, it will be possible to plant non-halophytic trees, shrubs and grasses. For UAE, a total of 76 halophyte species have been identified. Among these, 14 are seawater-tolerant halophytes, 29 as halophytes, 31 as semi-halophytes, and 2 are parasitic plants thriving on the roots of members of Chenopodiaceae and Zygophyllaceae family. The evaluation, domestication and large-scale utilization of native and introduced halophytes

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and salt-tolerant plant resources in sole or mixed farming system would have a significant impact on salinity control and remediation as well as on the economic development of salt-affected dry regions.

Keywords Halophytes · Marginal environment · Salt-affected areas · Dry salinity · United Arab Emirates

1 Introduction

Salinization of land and water resources is now widely recognized as a rising global problem to sustain agricultural production in arid and semiarid regions of the world (Ventura and Sagi 2013; Hasanuzzaman et al. 2014). Currently, about 1030 million hectares (Mha) are affected by twin problems of salinity and sodicity, of which about 412 Mha are affected by salinity and 618 Mha by sodicity (UNEP 1992; Wicke et al. 2011). However, these estimates do not present the area where both salinity and sodicity problems occur together. The salinity problems are encountered in all climates and are a consequence of both natural (*primary salinity*) and human-induced (*secondary salinity*) processes. Secondary salinity affects only 76 Mha, which are distributed in different continents highest being in Asia (53 Mha) (Dregne et al. 1991). Out of the total 76 Mha, 43 Mha are in irrigated lands of arid and semiarid regions of the world, whereas the rest 33 Mha are in nonirrigated lands. Secondary salinization has resulted due to poor water management practices in irrigated lands and by clearing of deep-rooted native vegetation in rainfed areas (Marcar et al. 1999).

The threat of soil salinization is also wide spread in the Middle East and North Africa (MENA) region, where 11% of the area is affected by soil salinity (Hussein 2001). Salt-affected soils vary in extent from 10% to 15% in Algeria to over 50% in Iraq. In Kuwait, more than 50% of the lands in the Euphrates plain in Iraq and Syria are seriously affected by salinization and waterlogging, and about 54% of the cultivated area in Saudi Arabia suffers from moderate salinization (Abdelfattah and Shahid 2007). In Egypt, 93% of the cultivated lands are affected by salinization and waterlogging, whereas salt-affected area in Iran has reached to 25 Mha (Qadir et al. 2008). In the United Arab Emirates (UAE), about 34% area is affected by salinity (EAD 2009). In the UAE, areas along the coastal sabkha (salt marshes or lagoonal deposits) are highly salinized (28.8 dS m^{-1}), whereas in the coastal region of the Abu Dhabi Emirate, salinity is more than 200 dS m^{-1} (Abdelfattah and Shahid 2007).

Salt-affected soils in the MENA region vary geographically with climate, agricultural activity, irrigation methods and policies related to land management and are mainly confined to irrigated farming systems in the arid and semiarid zones. The salts present are either of intrinsic origin (e.g. Egypt, Sudan and Iran), seawater intrusion (coastal regions) or irrigation from brackish groundwater. In the irrigated zones of Morocco, continuous irrigation with saline water has resulted in secondary soil salinization. In Libya, Sudan, Iran, Iraq, and UAE, large tracts of lands have been degraded due to heavy irrigation with groundwater for crop intensification. The situation is further complicated due to problems of waterlogging and high $CaCO_3$ (>90% in UAE). In the southern part of the Jordan Valley, soils are characterized by high salt content, poor permeability and high gypsum contents. Salinity, sodicity or the combination of both are seriously affecting productive areas like in the Nile Delta of Egypt and the Euphrates Valley in Iraq and Syria. In Kuwait and UAE, soil salinization is confined to coastal areas to larger extent and irrigated farms to a lesser extent. Salt-affected soils have been adversely affecting the growth of most plants with deleterious effects on crop yields.

There have been many responses in the region to contain the salinity threat such as direct leaching of salts, planting salt-tolerant varieties, domestication of native wild halophytes for agro-pastoral systems, phytoremediation (bioremediation), chemical amelioration and the use of organic amendments. In Iraq and Egypt, drainage systems have been installed to control rising water tables and arrest soil salinity. In Iran, Syria and other Gulf countries, crop-based management practices are used to combat salinization (Qadir et al. 2007). *Haloxylon aphyllum*, *Haloxylon persicum*, *Pteropyrum euphratica* and *Tamarix aphylla* (syn. *T. articulata*) are potential species for saline environments, whereas *Atriplex* is a potential fodder shrub for arid lands which could bring annual income up to 200 USD ha^{-1} (Koocheki 2000; Tork Nejad and Koocheki 2000). Salt tolerant crops (i.e. wheat, barley, sorghum) are also recognized as response management in saline environment.

Natural desert ecosystems (such as in UAE) are particularly vulnerable to climate change and desertification. Slight changes in temperature or soil moisture and dissolved salts regime could, therefore, substantially alter the composition and distribution of species. Increased frequency of climatic extremes and changes in soil salinity increase incursion of non-native annual plants, which significantly reduce productivity in arid ecosystems (Toderich et al. 2013). Afforestation has the potential to revegetate saline landscapes, provide valuable products to local pastoral communities from marginal degraded land and lower the elevated groundwater table via biodrainage (Heuperman et al. 2002; Marcar and Craw-Ford 2004; Khamzina et al. 2008). However, for sustainable outcomes, afforestation of saline lands must be preceded by a comprehensive evaluation of appropriate native and newly introduced tree species (Toderich et al. 2009). Utilization of native vegetation and revegetation can play an important role in raising oasis agriculture under saline environments (Gupta et al. 2009).

Over the last three decades, large amount of plant species that has the potential to survive in the harsh saline environment of UAE have been identified. Most recently, trend of growing arable crops in association with trees (agroforestry) has become popular. Because most trees are drought resistant, they are capable to provide fuel, fodder, fruit and other products even if the crops fail. This chapter reviews the information available on species of trees, shrubs, grasses and halophytes suitable for the saline soil and water conditions of the UAE. The prospects of agroforestry to improve productivity of desert ecosystems in the UAE is also discussed.

2 Socio-economic Benefits of Agroforestry

The practice of planting trees in salt-affected lands to increase profitability and potential side effects such as soil amelioration and controlling groundwater table rise was introduced in the nineteenth century. However, in the middle of twentieth century, the tree plantation became an integral part of agricultural production systems for the reclamation of saline lands. Agroforestry or agro-sylviculture is a land-use management system which combines shrubs and trees with agricultural crops or pasture to develop more diverse, profitable, healthy, ecologically sound and sustainable land-use systems. Kalinganire et al. (2008) defined "agroforestry as a deliberate integration of woody components with agricultural and pastoral operation on the same piece of land in a spatial or temporal sequence in such a way that both ecological and economical interaction occurs between them". Integrated system of trees and crops (Fig. 17.1) improves microclimate creating a cooler effect in hot summer days (Simons and Leakey 2004).

Agroforestry and intercropping are closely linked as both provide multiple outputs with a shared input. Agroforestry systems can be profitable over conventional agricultural and forest production systems because they offer increased productivity, economic benefits and more diversity in the ecological goods and services. Depending upon the application, impacts of agroforestry may include:

- Reducing poverty through increased production of wood and other tree products for home consumption and sale
- Contributing to food security by restoring the soil fertility for food crops

Fig. 17.1 A typical example of integrated agroforestry system

- Cleaner water through reduced nutrient and soil runoff
- Countering global warming and the risk of hunger by increasing the number of drought-resistant trees and the subsequent production of fruits, nuts and edible oils
- Reducing deforestation and pressure on woodlands by providing farm-grown fuelwood
- Reducing or eliminating the need for toxic chemicals (insecticides, herbicides, etc.)
- Increased crop stability
- Stabilize depleted soils from erosion
- Bioremediation

In addition, agroforestry may also help in achieving associated environmental goals, such as:

- Carbon sequestration
- Odour, dust and noise reduction
- Green space and visual aesthetics

For arid regions such as Australia, Africa and Middle East, establishment of desert agroforestry as a mainstream agricultural technique can help in increased food production due to the successful growth of specific crops that are well-suited to the dry and hot environment and prevention of desertification. The integration of trees into the cropping system help in increasing system productivity by reducing nutrient losses through leaching in deep soil and reduced soil erosion (Dove 2003). Trees may increase the overall system productivity by increasing nutrient availability through nitrogen fixation and deep rooting and their enlarged absorptive capacity associated with mycorrhizae and fungal infection. The improvement of soil fertility by trees has been confirmed in studies which compare productivity of crops grown on soils formed under tree canopies and on soils in open areas (Craig and Wilkinson 2004; Botha 2006). Generally, higher soil nutrient status under tree cover is reflected in the mineral content of understorey herbaceous species (Tonye et al. 1997).

The primary processes which contribute to higher fertility around trees are related to enhanced biological processes associated with the seasonal and long-term return of nutrients accumulated in trees to the soil through litter fall, root decay and exudation and their mineralization, as well as leaching of nutrients stored in canopies. Soil texture sometimes differs according to tree size although the reasons behind these variations are not clearly understood. Due to increases in organic matter and improved microclimatic conditions, trees enhance soil microbial and enzymatic activity, decomposition and physical characteristics (Tian et al. 2001). Trees can also help in controlling soil loss through wind erosion and increase soil nitrogen availability due to nitrogen fixation (N’goran et al. 2002).

3 Agroforestry in Marginal Environments

Marginal environments include areas where soil and water-quality is low for potential crop production. Marginal lands have poor permeability, high salt contents, shallow water table conditions and other associated problems which restrict agricultural production. These lands are distributed in the entire world, regardless of climatic conditions and geographical occurrence. However, the criteria of marginality may vary based on their specific use (Anderson 2012). Most conservative estimates suggest that about 10% of the total arable land in the world is affected by salinity and sodicity extending into more than 100 countries and almost all continents (Wicke et al. 2011). In the Middle East, 11% of its area is affected by soil salinity, and agriculture is constrained due to shortage of good quality soil and water. Therefore, percentage of population engaged in agriculture is very low, i.e. ranging from less than 1% in Qatar to 29% in Oman. Consequently, the contribution of agriculture in the total GDP of these countries is also less than 1%.

The major causes of land degradation in the Middle East include use of brackish groundwater for irrigation, insufficient leaching of salts and upward movement of saline groundwater in the very hot environments. Rising sea levels along with the over-exploitation of fresh water resources also cause seawater intrusion in coastal zones. Increasing pressure on land resources to grow more food, rising living standards, fast depletion of fresh water resources and poor management practices have further aggravated the problem. Therefore, there is every motivation to designate more capital and efforts to reclaim degraded soils to ensure future food security for the fast-growing population of different regions especially in the Middle East.

Sustainable agricultural production from marginal lands can be attained by adopting integrated natural resource management approach. This approach includes all aspects of soil, water, plants and climate to find long-term sustainable solutions for the marginal lands and waters. The *biosaline agriculture* is one of the promising approaches to deal with these situations. This approach develops cropping systems for saline environments, using the capacity of certain plants to grow under saline conditions in combination with better soil and water management practices. This approach suggests combination of physical, chemical, hydrological and biological methods considering land, water and environmental conditions of a specific location (Hamed et al. 2014). Physical methods include land levelling, salt scrapping, tillage and subsoiling, whereas hydrological interventions could be the introduction of efficient irrigation systems such as drip, sprinkler, sub-surface irrigation, etc. Use of chemical soil amendments to rectify soil sodicity problem, calculations of leaching requirements for saline soils and development of salt tolerant crops, forages and trees are some useful approaches for transforming marginal soils into productive lands (Shahid and Rahman 2011).

The *biosaline* approach helps in reclaiming saline lands through the cultivation of salt-tolerant cereal and forage crops and plantation of trees. Plantation of salt-tolerant trees in combination with the salt tolerant plants is an economically beneficial proposition for saline areas. Trees can be used for timber, pulp, firewood, fodder (e.g. *Acacia nilotica*, *Acacia saligna*), cut flowers, honey and other products (e.g. leaf oils and tannins); shelter and shade; wind, soil and erosion control; wildlife corridors; and aesthetics. In addition, trees also act as windscreens, add organic matter and nitrogen and improve soil structure by breaking hard pans.

The proper selection of plant species is the key for productive agroforestry because different crops and trees show varying reactions to salinity stress. For example, wheat tolerate very low values of salinity and then drop productivity instantly once threshold salinity levels are achieved. On the other hand, salt-tolerant trees continue to thrive under increasing salinity levels, and some halophytes (salt-loving species) even show an increase in productivity with increasing levels of salt. However, for most *biosaline* tree species, salt-tolerance data is still non-existent or incomplete. Salt tolerance of trees is difficult to quantify because it varies considerably with many environmental and plant factors. Most of the trees are less salt tolerant during seed germination and become progressively more tolerant in later growth stages.

The use of shrubs and grasses depends upon the choice of species regarding prevailing edaphic and climatic conditions of the area. Under good to moderate environmental conditions, shrub species could be used primarily for forage and fodder purposes. Both shrubs and grasses have successfully and widely used for amelioration and reclamation of problem soils and for lowering shallow water tables (Sandhu and Qureshi 1986; Ahmad and Ismail 1993; Barrett-Lennard and Galloway 1996; Toderich et al. 2013). Some genera, such as *Prosopis*, *Tamarix* and *Atriplex*, occur naturally on salt-affected soil and/or within or near coastal or inland sites where soils or groundwater is saline. These genera contain species termed as halophytes which have evolved through several salt-tolerating mechanisms. A list of selected salt-tolerant tree and shrub species commonly used for marginal environments are given in Table 17.1.

4 The Case of United Arab Emirates (UAE)

The United Arab Emirates (UAE) is in the south-eastern part of the Arabian Peninsula and borders Oman and Saudi Arabia (Fig. 17.2). The total area of the country is 82,880 km^2. Abu Dhabi is the largest of seven Emirates and accounts for 87% of the total land mass of the country (Soil Survey of Northern Emirates 2012). The main characteristics are limited arable land, harsh climate and poor renewable water resources. The landscape of the UAE is dominated by low-lying, sandy desert, but extensive salt flats (sabkha) occur in coastal areas. The climate is arid to hyper-arid, characterized by high temperatures and low rainfall. Groundwater quality is extremely poor, ranging between 15 and 30 dS m^{-1}. The climate is arid to hyperarid, characterized by high temperatures and low rainfall. The summers (May to October) are distinctly hot, with daytime temperatures regularly exceeding 40 °C. Rainfall occurs occasionally during the summer but is generally restricted to the cooler winter months (November to April). Temperatures can drop to 4 °C in some areas at

Table 17.1 Rating of selected tree and shrub species to root-zone soil salinity, sodicity and waterlogging

Species	Salinity (EC_e in dS m^{-1})	Sodicity	Waterlogging
*Acacia ampliceps**	Severe	Severe	No
*A. auriculiformis**	Moderate		Yes
A. cyclops	High		
A. machonochiena	Severe	Severe	
A. nilotica	Moderate	High	
A. salicina	High	High	
A. saligna	Moderate	Moderate	
A. stenophylla	Severe	Severe	Yes
A. tortilis	Moderate		
Ailanthus excelsa	High	Moderate	
Albizia lebbeck	Moderate	Moderate	
A. procera		Moderate	Yes
Azadirachta indica	Moderate		
Butea monosperma	Moderate	High	
Casuarina cristata	Moderate/high	Moderate	Yes
C. cunninghamiana	Moderate/high		Yes
C. equisetifolia	Moderate	High	Yes
*C. glauca**	High	Moderate/high	Yes
*C. obesa**	High/severe	High	
Capparis aphylla	High		
Conocarpus lancifolius	High		
Dalbergia sissoo	Moderate	Moderate	
Eucalyptus brassiana	Moderate/high		
*E. camaldulensis**	Moderate	High	Yes
E. citriodora	Moderate		
*E. grandis**	Slight/moderate		Yes
E. coolabah	Moderate	High	
E. moluccana	Moderate		
*E. occidentalis**	High		
E. platypus	Moderate	Moderate	Yes
E. raveretiana	High		
E. robusta	Moderate		
E. rudis	High		
E. spathulata	High	Moderate	Yes
*E. tereticornis**	Moderate	High	Yes
Leucaena leucocephala	High	Moderate	
Melaleuca arcana	Moderate		
M. bracteata	Moderate	Moderate/high	Yes
M. halmaturorum	Severe	Moderate	Yes
M. lanceolata	High		Yes

(continued)

Table 17.1 (continued)

Species	Salinity (EC_e in dS m^{-1})	Sodicity	Waterlogging
M. leucadendra	High		Yes
M. quinquenervia	Moderate	Low	Yes
Parkinsonia aculeata	Moderate		Yes
Pinus halepensis	Moderate		
Pongamia pinnata	Moderate		
Populus euphratica	Moderate		
Prosopis chilensis		High	
P. juliflora	Severe	High	Yes
Sesbania formosa	Moderate		Yes
S. grandiflora	Moderate		Yes
Tamarix articulata	Severe		Yes
T. articulata	Severe		Yes
Terminalia arjuna	High	Moderate/high	
Ziziphus jujuba	High		Yes
Z. spina-vulgaris	High		Yes

Salinity is expressed as EC_e [moderate (4–8), high (8–16), severe (>16) dS m^{-1}]. Sodicity is expressed in terms of pH [moderate (8.0–9.0), high (9.0–10.0) and severe (>I0.0)]. Species marked with an asterisk (*) are known to exhibit marked provenance response on saline soils

Modified from Marcar et al. (1999). + In literature *Tamarix articulata* and *T. aphylla* are synonyms

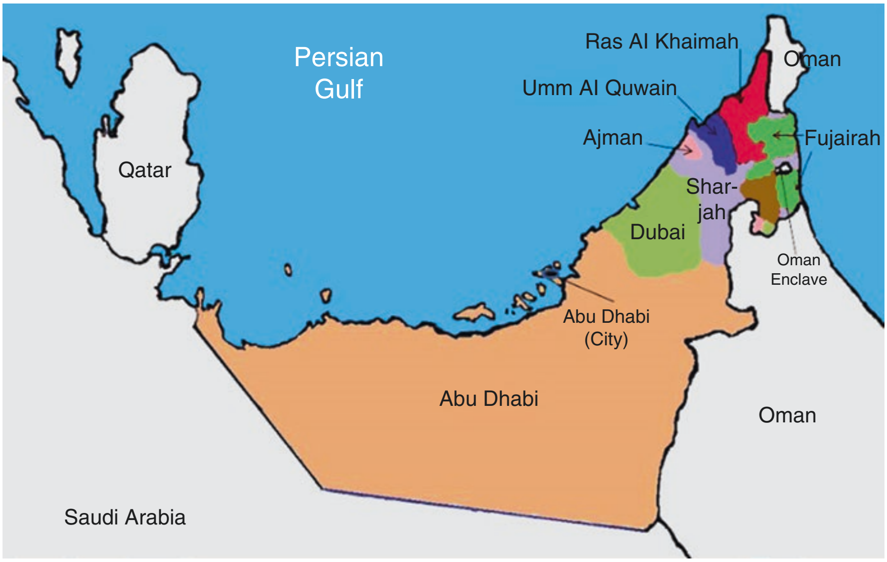

Fig. 17.2 Map of United Arab Emirates

Table 17.2 Measurements of salinity and pH on UAE farms and various *sabkhas*

	Soil salinity in farms		Soil salinity in sabkhas	
Location	pH	EC (dS m^{-1})	pH	EC (dS m^{-1})
Abu Dhabi	7.1–9.0	4.0–38.0	8.0	73.0
Dubai	7.1–9.0	1.0–38.0	8.6	231.0
Sharjah	9.0–9.8	0.2–10.8	9.1	67.4
Ajman	8.9–9.2	1.4–3.0	8.1	116.9
Umm al-Quwain	8.2–8.5	2.5–4.2	7.7	15.6
Ras al-Khaimah	4.2–8.9	0.7–17.7	8.5	191.6
Al Ain	0.5–27.0	7.7–9.4	8.0	300.0
Tarif	8.0	82.0	7.2	213.0
Sabkhat Matti	7.8	98.0	6.6	219.0
Fujairah	8.0–9.9	0.5–10.5	8.4	74.0

night, but frosts are unknown. Annual rainfall amounts vary according to location, but precipitation generally decreases along a northeast to southwest gradient. The mountainous areas in the east receive most rainfall (long-term annual mean of about 154 mm in Masfut, ranging from 4 to 479 mm per year), about 80 mm in coastal areas such as Abu Dhabi and Dubai, but substantially less in more western and southern parts of the country.

The extent of soil salinization in the UAE has changed over time. In 1994, FAO estimated that about 12% of the total land area is salinized. However, more recent estimates suggest that area affected by salinity is about 25%, and salinity of some areas has gone so high that only halophytic plants can be grown. The total dissolved solid (TDS) concentrations vary from 500 to 6000 ppm for most agricultural systems (Karim and Dakheel 2006). However, TDS concentrations can be as high as 12,000 ppm on forage (Rhodes grass – *Chloris gayana*) grown areas and up to 15,000 ppm where indigenous plants such as *Prosopis cineraria* and *Acacia tortilis* are grown. This is mainly due to the use of highly saline groundwater (>15,000 ppm) for irrigation. On the other hand, salinity on many UAE farms is very high, especially on older farms ranging from 15 to 20 dS m^{-1}. As a result, many of the country's old farms have been abandoned. The variations in the soil salinity and pH values in extreme *sabkhas* of UAE are shown in Table 17.2.

The UAE soils can be divided into the following three categories for plant growth (Karim and Dakheel 2006):

- *Farmlands salinized due to poor irrigation practices*: These lands need leaching of salts using fresh water to grow conventional crops. Therefore, growing salt-tolerant crops on these lands without any intervention is worth serious consideration.
- *Arid lands with brackish groundwater*: Growth of sensitive crops is restricted in these areas; however, these lands have the potential to grow selected salt-tolerant crops by applying special cultural techniques and using brackish groundwater for irrigation.

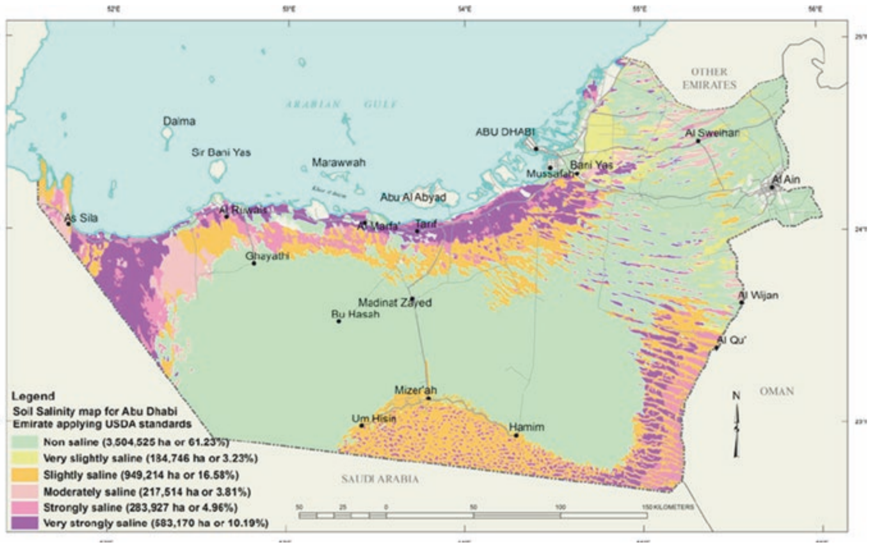

Fig. 17.3 Soil salinity map of the UAE

- *Coastal deserts*: In the extensive coastal area of the UAE, most farmers are reluctant to grow crops/plants because soils are extremely sandy and only seawater is available for irrigation. In these areas, growing halophytes and highly salt-tolerant plants which have the potential can generate significant income for the farmers.

  Soil salinity map of UAE is depicted in Fig. 17.3

Salt-tolerant plants and halophytes found on seashores and estuaries have many potential uses such as food, fibre, fuel and medicines. Due to these advantages, their potential use in the UAE is getting momentum. Many salt-tolerant genotypes of food crops have been identified, which can grow in these marginal environments. These include carrots, melons, onions, tomatoes, date palm, pearl millet, barley, sorghum, maize and wheat. Many naturally occurring plants also have the potential of being utilized as human food. These salt-tolerant food crops can be grown successfully using saline groundwater to achieve economical returns. The salt-tolerant genotypes of food plants offer the same value as traditional food crops.

Halophytic and salt-tolerant grasses, shrubs and trees are excellent sources of fodder. Grasses such as *Chloris gayana* (Rhodes grass), *Panicum turgidum*, *Pennisetum* spp., *Lasiurus* spp. and many trees and shrubs have also been used for grazing. Perennial salt bushes (*Atriplex* spp.) and forage herbs like *Medicago* spp. *and Trifolium* spp. are tolerant to both soil and water salinity and can grow throughout the UAE. Salt-tolerant trees such as *Acacia* spp., *Leucaena leucocephala*, *Prosopis cineraria* and *Prosopis juliflora* are best suited for use as windbreaks and additional sources of fodder for livestock, which consume their pods, leaves and branches.

The salt-tolerant plants such as *Hibiscus* spp., *Juncus* spp., *Typha* spp. and *Phragmites australis* are also used as suitable fibre sources. The latter is a marsh plant and commonly used for fencing, roofing, basket making and fuelwood. The branches of *Sesbania bispinosa*, a well-known salt-tolerant legume and fodder crop, are also widely used as a fuel and fibre. Salt-tolerant plants such as *Tamarix*, *Casuarina*, *Acacia*, *Prosopis*, *Eucalyptus*, *Avicennia* and *Rhizophora* are commonly used as fuelwood. Medicinal use of local plants is also very popular in UAE. These plants have proven to be effective in treating certain illnesses, such as diabetes, arthritis, high blood pressure, skin diseases and urinary tract disorder (Karim and Dakheel 2006).

4.1 Agroforestry in the UAE

In the UAE, integrating trees and shrubs with other farm enterprises has also been introduced to generate additional income as well as increasing the system's productivity. The pioneer work in this regard has been carried out by the International Center for Biosaline Agriculture (ICBA) over the past decade. *Acacia ampliceps* grows well in UAE ecology (Fig. 17.4). ICBA has studied the feasibility of *A. ampliceps* for Central Asia to North Africa regions. The plant is found to fix atmospheric nitrogen, provides forage/fodder for animals and fares well with other companion species, as well as a potential source for bioenergy. ICBA's research over the past 6 years has demonstrated the compatibility between *A. ampliceps* and two salt-tolerant grasses, *Sporobolus arabicus* and *Paspalum vaginatum*, in response to different salinity and fertilizer treatments.

Fig. 17.4 Growth of *Acacia ampliceps* at the ICBA experimental farm

Field studies conducted on UAE soils have shown that *Acacia ampliceps* can fix nitrogen under different salinity levels (10–30 dS m^{-1}), thus supporting the nutrient requirements for the two grasses, i.e. *Sporobolus arabicus* and *Paspalum vaginatum* (Toderich et al. 2013). Based on average values over the study period, the unfertilized plots showed a 7–13% reduction in biomass yields for *Sporobolus arabicus*, but insignificant difference for *Paspalum vaginatum*. The average yield of these grasses varied from 22 to 28 Mg dry matter ha^{-1} $year^{-1}$. In addition, the foliage from the trees harvested at 2 m from the ground surface additionally provided ~10 Mg of dry matter ha^{-1} $year^{-1}$. The *A. ampliceps* trees showed nodulation even at 30 dS m^{-1} with the bacteria showing the characteristic feature of gram-negative *Rhizobium*. The fixation of nitrogen by the *Acacia* trees helps in increasing the soil nitrogen through the root system and supporting the forages.

ICBA has also evaluated different kinds of plants in marginal quality water for agroforestry systems, such as alley cropping, silvopasture, windbreaks, riparian buffer strips and forest farming for non-timber forest products. These integrated trees and shrub systems are considered as an additional source of income and enhanced productivity of lands through nutrient and water management. An additional benefit of the agroforestry system is better nutrient management since absence or loss of nutrients significantly affects the productivity of plants. Under marginalized situations, the success of any type of production system will depend on the cost-benefit ratio, and hence a stable biological system that can manage nutrient efficiently adds economic benefits. In general, tree species are grown with other crops and/or other shrubs/forbs.

The most commonly used alley cropping system is an agricultural practice in which agricultural crop is grown simultaneously with a long-term tree crop. The purpose is to enhance income diversity (both long and short range), reduce wind and water erosion, improve crop production and utilization of nutrients, improve wildlife habitat or aesthetics and/or convert cropland to forest. The practice is especially attractive to landowners wishing to add economic stability to their farming system while protecting soil from erosion and water from contamination and improving wildlife habitat. When designing an alley cropping practice, considerable thought must be given to which trees and crops will be grown together and at what spacing. Because of the interaction between the tree and crop components and the goal of optimizing economic gain, a mix of trees and companion crops should be created that provides the highest return on the investment. There are many tree and crop combinations that can be practiced under this practice. This system generally uses four basic groups of companion crops. These include:

- *Row/cereal crops* (corn, soybeans, wheat, barley, oats, potatoes, peas, beans).
- *Forage crops* (fescue, orchard grass, desmodium, bluegrass, ryegrass, brome, clover, alfalfa). The production of many forages may be enhanced in the shade of an alley cropping practice.
- *Specialty crops* (landscape plants like blue spruce, dogwood, redbud; Christmas trees; small fruit trees; or crops like goldenseal or ginseng)
- *Biomass crops* (trees including poplars, willows, silver maple, birches) (herbaceous crops like switch grass)

For successful agroforestry systems, the tree selection depends on the goals, objectives and priorities. Ideally, the tree species should have high commercial or environmental value and the capacity to create suitable micro-environments for the companion agricultural crops. Alley cropping practices are highly diverse and range from simple to complex. The knowledge of the growth characteristics of trees and the companion crops is useful to determine whether trees should be planted in single or multiple rows and whether single or mixed species should be used. Growers also need to understand that growth rates of different species may conflict, especially when species are mixed in the same tree row. If not properly designed, one or more species may dominate the site and have a negative effect in mixed species plantings.

4.2 Halophytes for Agroforestry in the UAE

Halophytes are plants that have the capacity to tolerate high levels of salts and/or sodium in soil or in irrigation water. These plants are very suitable in protecting habitats, maintaining ecological stability and developing agriculture and habitat restoration in salt-affected soils. These plants are more dominant in saline coastal and inland soils of arid and semiarid climates, where evapotranspiration is exceedingly higher than the precipitation (Manousaki and Kalogerakis 2011). Halophytes can grow in different habitats (marshes, estuaries, cliffs, dunes, etc.) and constitute about 1% of the world's flora (Flowers and Colmer 2008). Facultative halophytes can also grow under fresh water conditions, while obligate halophytes need salts to survive. These plants can tolerate salinity by adjusting their internal water relations through ionic compartmentation in cell vacuoles, accumulation of compatible organic solutes, succulence and salt-secreting glands and bladders (Shabala and Mackay 2011). Halophyte species can remove the salts from salt-affected soils through salt excluding, excreting or accumulating by their morphological, anatomical and physiological adaptations in their organelle level and cellular level (Hasanuzzaman et al. 2014). Halophytic plants can also be a promising candidate for the removal of heavy metals from normal and hypersaline soils (Manousaki and Kalogerakis 2009; Nedjimi and Daoud 2009).

The UAE has extensive salt flats (sabkha) in the coastal areas. In the east, the Hajar Mountains rise sharply above the surrounding landscape to an elevation of 2000 m (Fig. 17.5). Temporal variation in the seasonal rainfall pattern has a decisive influence on biological activity. Coastal regions experience high humidity, especially in the summer months, but the interior has a much drier climate. Mists frequently cover the mountains and some desert areas, such as to the south and west of Abu Dhabi island. Dewfall is a common phenomenon in coastal localities, and many plants on coastal dunes have shallow, lateral rooting systems that enable them to exploit this regular input of moisture. Under these circumstances, establishment of halophytic plants such as *Atriplex* species can be advantageous due to low annual maintenance costs and their ability to survive high salt contents in the soil. As conditions become less severe, it will be possible to plant non-halophytic trees, shrubs and grasses.

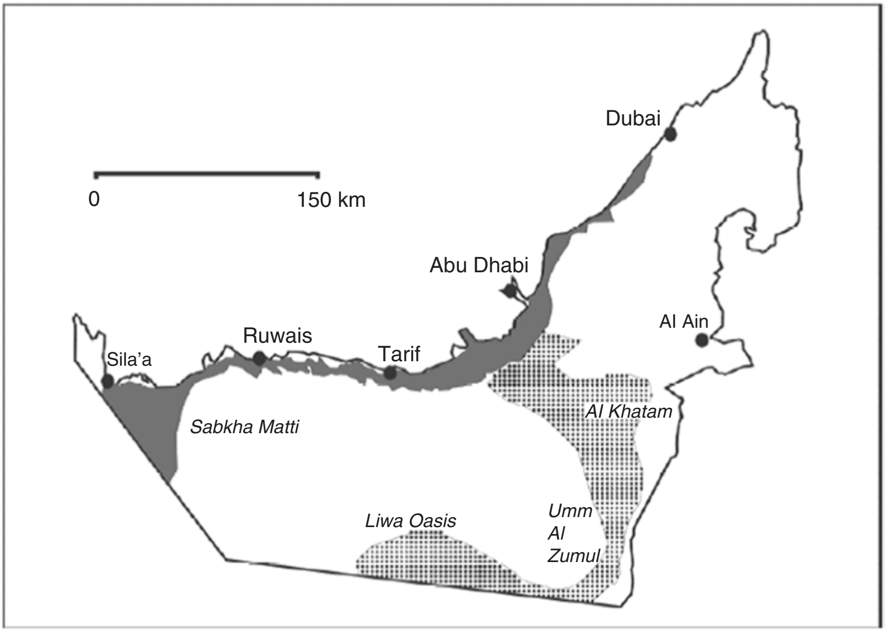

Fig. 17.5 Map of UAE showing the extent of coastal sabkha (grey shaded area) and Sabkhat Matti, as well as areas with inland sabkhat (dotted area)

Due to high salt content and lack of fresh water resources, sabkha is an adamant environment for biological activity and supports virtually no higher plants (Barth and Böer 2002). However, halophytes can inhabit thin layers of aeolian sand that is deposited on the sabkha surface due to local weather conditions, which can support dense vegetation (Gairola et al. 2015). A major problem with halophytic vegetation in this part of the world is the taxonomic uncertainty surrounding certain taxa, as well as the fact that many species involved are easily confused and often misidentified (Brown 2006). For instance, some members of the Chenopodiaceae display significant morphological variation, and it is often difficult to reasonably describe key features that may help separate one specie from another. This problem also applies to other genera.

Many species of halophytic plants such as *Suaeda maritima*, *Sesuvium portulacastrum*, *Arthrocnemum indicum*, *Suaeda fruticosa*, *Tamarix aphylla*, *Atriplex nummularia* and *A. halimus* have been used to clean contaminated soils as they can absorb more salts in their tissues, thereby reducing salts from the saline land (Ravindran et al. 2007; Nasir 2009). These plants are also considered useful for the reclamation of salt-affected soils. Glenn et al. (2013) indicated that halophytes can maintain high productivity of agricultural lands up to a root-zone salinity of 70 g l^{-1} TDS, double the salinity of seawater. However, this would require frequent irrigation to keep the shallow-root zone at field capacity and precise calculations of leaching requirements to prevent accumulation of salts. Öztürk et al. (2014) has shown that species like *Cynodon dactylon*, *Ruppia maritima* and *Inula crithmoides* can produce biomass through *biosaline* agriculture. Similarly, *Salicornia europaea*, a high-quality edible oil-yielding plant with high economic value, can be effectively used to reclaim highly salinized soils (Muscolo et al. 2014).

In the Arabian Gulf region, hundreds of terrestrial halophytes are grown on seawater or in hypersaline salt marshes, where salinity levels are usually higher than seawater. Some of the important halophyte species include *Arthrocnemum macrostachyum*, *Atriplex farinosa*, *Halopeplis perfoliata*, *Halocnemum strobilaceum*, *Salicornia europaea*, *Suaeda maritima*, *Suaeda vermiculata*, *Salsola imbricata*, *Zygophyllum mandavielli*, *Tamarix aphylla*, *Haloxylon persicum*, *Sesuvium verrucosum*, etc. Based on the literature review, Böer (2002) has identified 76 plant species of halophytes for UAE. Among these, 14 are seawater-tolerant halophytes, 29 as halophytes, 31 as semi-halophytes, and 2 are parasitic plants thriving on the roots of members of Chenopodiaceae and Zygophyllaceae family. Similarly, Böer and Al Hajiri (2002) have identified 49 halophytes for Qatar, including one mangrove species, 12 as seawater-tolerant halophytes (high salinity tolerant), 17 as halophytes (tolerant to salinity), 20 as semi-halophytes (tolerant to salinity, but probably dependent on brackish to fresh water for normal development) and 2 are parasitic plants thriving on the roots of true halophytes.

Halophytic plants vary in the degree of their salt tolerance and the way they regulate salt content in their tissues. Therefore, it is imperative to explore the morpho-anatomical adaptations and physiological significance of the halophyte species of the Arabian Peninsula. Many of the halophytes of the Arabian Peninsula are growing even in hypersaline sabkha (salt marshes), where salinity reaches several folds greater than the seawater salinity (EAD 2012). However, more research is needed to understand structure and function of salt glands, nature of secreted material, mechanism(s) of ion secretion and the way halophytes handle salts. This may help in selection of the best halophytic species for bio-reclamation of salt-affected soils in arid and semiarid regions of the Arabian Peninsula (Shabala 2013).

In the context of reclamation of salt-affected soils, the halophytic vegetation of Arabian Peninsula seems highly diversified, and it is likely that the halophytic flora possesses a wide range of useful features of salt tolerance. In addition, Cybulska et al. (2014) highlighted that halophyte species of UAE are a source of unique active phytochemicals, potentially due to the extreme environmental conditions under which the plants grow, and have great potential to be used as raw material in biorefinery processes where biofuel production from the plants macronutrients (carbohydrates) is combined with the production of value-added products. The most frequently used halophytes used in the coastal areas of Abu Dhabi are given Table 17.3.

A total of 59 plant species (without irrigation) were identified along the Abu Dhabi Gulf coast, of which one is classified as a true mangrove and three are classified as true salt marsh species. There are another 55 plants species, but these species are neither mangrove nor salt marsh. Vegetation of sandy beaches or “storm berms” was classified as sand sheet vegetation and others as vegetation of brackish ground or rocky headlands. In most areas, the coastal vegetation forms only a narrow band, which is separated from true terrestrial vegetation by a wider band of coastal sabkha.

Table 17.3 Plant species along the Abu Dhabi coastline and the ecosystems in which they occur

Species	Major ecosystem	Species	Major ecosystem
Suaeda fruticosa	SS	*Phoenix dactylifera*	SS
Prosopis cineraria	SS	*Pluchea dioscoridis*	BW
Arthrocnemum macrostachyum	SM	*Sesuvium verrucosum*	BW
Salsola drummondii	SS	*Aeluropus lagopoides*	BW
Halopeplis perfoliata	SS	*Arundo Donax*	BW
Avicennia marina	M, SM	cf. *Cymbopogon* sp.	SS
Halocnemum strobilaceum	*SM*	*Dipterygium glaucum*	SS
Suaeda vermiculata	SM	*Helianthemum lippii*	H
Zygophyllum qatarense	SS	*Lotus garcinii*	H
Anabasis setifera	SS	cf. *O. compressa*	BW
Bienertia cycloptera	SS	*Taverniera spartea*	H
Salsola imbricata	SS	*Calligonum comosum*	H
Zygophyllum mandavillei	SS	*Euphorbia serpens*	BW
Cyperus arenarius	SS	*Heliotropium dyginum*	SS
Heliotropium bacciferum	SS	*Lasiurus scindicus*	H
Cornulaca monacantha	SS	*Leptadenia pyrotechnica*	SS
Limonium axillare	SS	*Limeum arabicum*	SS
Prosopis juliflora	SS	*Pennisetum divisum*	SS
Tamarix sp.	BW	*Phyla nodiflora*	BW
Cyperus conglomeratus	SS	*Sesuvium portulacastrum*	BW
Salsola c. Cornulaca	H	*Sporobolus iocladus*	SS
Salvadora persica	BW	*Haloxylon salicornicum*	H
cf. *leucocantha*	SS	*Seidlitzia rosmarinus*	SS
Halopyrum mucronatum	SS	*Shpaerocoma aucheri*	SS
Panicum turgidum	SS	*Ipomoea pes-caprae*	BW
Phragmites australis	BW	*Suaeda aegyptiaca*	SS
Atriplex leucoclada	SS	*Zygophyllum simplex*	SS
Stipagrostis sp.	H	*Chloris* sp.	BW
Sporobolus spicatus	BW	*Farsetia* cf. *aegyptiaca*	H
Dactyloctenium scindicum	SS		

Source: Böers and Saenger (2006)
H (rocky) headlands, *SS* sand sheets, *M* mangrove, *SM* salt marsh, *BW* brackish water

5 Conclusions and Recommendations

The world's most productive lands have already been utilized, and the need to use marginal lands of lower quality is increasing to ensure food security and environmental sustainability. This requires careful evaluation of available land resources about their location, quality and production potential. In most of the GCC countries, suitability of lands for irrigated agriculture is very limited, e.g. in the Abu Dhabi Emirate, only 5.4% of the available land is suitable for irrigation farming. The other major obstacle to promote irrigated agriculture in the UAE is the lack of fresh water resources. Therefore, it is imperative to develop plant species that can grow under marginal conditions.

Over the last three decades, considerable work has been done in identifying crops, trees, shrubs and grasses that can potentially grow under marginal environments of the UAE. The major benefits of using trees, shrubs and grasses on salt-affected and/or high saline water table soils are that they can help in lowering water tables through either control of accessions to or withdrawal from groundwater and use saline drainage water or pumped groundwater. Many salt-tolerant species identified have the capacity to use groundwater up to an EC of 10 dS m^{-1} without marked reductions in their transpiration rate. The amount of groundwater used by plants depends on tree density, the proportion of the area planted, crown cover, root architecture, soil hydraulic characteristics and groundwater dynamics. There are, however, concerns that the control of groundwater table through tree plantation is effective only in the short to medium term because of the inflow of salts in the root zone.

In the UAE, tree production systems can be of great value for agroforestry because of the presence of sandy soils and saline groundwater. However, the success of these plantations will depend on the effectiveness of plant species grown for the management of salt concentrations in the root zone and the concentration of sodium carbonate in the irrigation water. Since leaching fractions for the sandy soils are high, areas with deeper water tables will be most suited for these plantations. Incorporation of fodder halophytes into the agro-silvopastoral system or domestication of wild halophytes represents low-cost strategies for rehabilitation of desert degraded rangelands and abandoned farmer lands affected both by soil and water salinity. Salt-tolerant crops cultivated into an agro-silvopastoral model benefit from the improvement of soils and microclimatic conditions provided by the shrubs.

Promoting sustainable use of marginal land and water resources for food-feed crops and forage legumes will assist to improve food security, alleviate poverty and enhance ecosystem health in smallholder crop-livestock systems. It will also contribute to make farmers more resilient against climate change. The evaluation, domestication and large-scale utilization of native and introduced halophytes and salt-tolerant plant resources in sole or mixed farming system would have a significant impact on salinity control and remediation as well as on the economic development of salt-affected dry regions. Planting herbaceous fodder crops between fruit and fodder trees on intensive agroforestry plantations leads to increase the productivity of degraded lands. The agroforestry concept may also help in on-farm drain water management, thus solving the problems of saline drainage water effluent. This will create favourable conditions for the desert and semi-desert areas as viable farming regions.

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Chapter 18
Enhancing Fodder Productivity on Salt-affected Lands in Arid and Semiarid India

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Abstract Soil salinity/alkalinity is an important factor adversely affecting the soil health and plant productivity under arid environment. In India, 6.73 m ha area is reported to be salt-affected out of which about 50% (2.98 mha) occurs in Rajasthan, Gujarat, Haryana, and Punjab. Salient findings of research done on lithic, calcid, coarse sandy to loamy sand salty soils in Jodhpur, Rajasthan, and silty black highly saline soils of Little Rann of Kachchh in Gujarat to find out suitable plant species and planting practice to increase the production are discussed. Shrubs of genus *Atriplex* performed well with FYM and nitrogen. These produce nitrogen-rich fodder used for sheep and goat in Rajasthan. The indigenous multipurpose halophytic tree, *Salvadora persica*, maintained 66.7–85.2% survival after 10 years. Gypsum + 9g N treatment gave best growth and biomass results. While on black soil, wheat husk (WH), FYM, and urea gave best results. *Acacia ampliceps* (Australian tree) recorded 76% survival on gypsum-treated deep alkali soils (60–75 cm depth) and yielded two-fold biomass (12–5.43 kg tree^{-1} for gypsum treated and 8.1–3.9 kg tree^{-1} for untreated trees on deeper and shallow soils) at the age of 5 years. Its growth was much faster with WH and FYM on black soil, but it suffered under drought and extreme hot conditions where *Acacia bivenosa* was more suitable. *Suaeda nudiflora* from mud flats and seashore adapted well (55–80% survival) on sandy saline soil after 72 months. *Colophospermum mopane* (a south central African tree) maintained 89% overall mean survival after 5 years (86.5% in control and 92.1% on circular dish mound, *CDM*). Overall, plants on CDM recorded a mean 1.45 kg green biomass yield plant^{-1} which is 5.9% more compared to control plants (1.37 kg), the difference was 9.1% for leaf and 5.2% for branch component. Roots penetrated nodulated $CaCO_3$ layer. Double-ridge and circular dish mounds enhanced the survival of all the plant species by providing protection from waterlogging and less salty environment. Crescent-shaped drainage trenches helped in leaching. Plantation activities improved the site condition and promoted growth of indigenous vegetation. Natural germination of *S. persica* was observed on sandy soil in Rajasthan to an extent that it suppressed the growth of *Prosopis juliflora.* All the exotic species

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adapted well, flowered, and produced viable seed resulting in natural germination. They did not suppress the growth of indigenous salt-tolerant grasses such as species of *Sporobolus* and *Chloris*.

Keywords Salt-affected soils · Arid and semiarid · Survival · Biomass · Gypsum · Nitrogen · Urea · Wheat husk · Mound practices

1 Introduction

The distribution of salt-affected soils is relatively more extensive in the arid and semiarid regions compared to the humid regions. Salts occur naturally in all soils. Rain dissolves these salts, which are then swept through streams and rivers to the sea. Where rainfall is sparse or there is no quick route to the sea, some of this water evaporates, and the dissolved salts become more concentrated. In arid areas, this can result in the formation of salt lakes or in brackish groundwater, salinized soil, or salt deposits. These lands would require large (and generally unavailable) amounts of water to leach away the salts before conventional crops could be grown. The term salt-affected refers to soils that are saline or sodic, and these cover over 800 million hectares. According to the FAO land management and nutrition service, over 6% of the world's land (Table 18.1) is affected by either salinity or sodicity. High levels of salts in soils reduce plant growth and crop yield in many ways. There may be direct toxic effects, especially from elements like sodium, chlorine, or boron. Ionic imbalances may also occur in plants. Similarly, plants may also suffer from physiological drought as water availability to plants is lowered due to the high osmotic potential of salty water in the soil solution (FAO 1988).

In the absence of favorable conditions for agriculture, livestock rearing is the alternative source of livelihood for majority of rural population in arid zone. It has been observed that in the region, every farm family keeps herd of 15–20 animals which sustains on crop residues and grazing on fallow lands (Gupta 2000). The area cultivated for fodder amounts to 4% of the total cultivable area. However, exclusive pastures and grasslands are widespread and are grazed by domestic animals. The

Table 18.1 Regional distribution of salt-affected soils (million ha)

		Saline soils		Sodic soils	
Regions	Total area	Area	%	Area	%
Africa	1899.1	38.7	2.0	33.5	1.8
Asia, the Pacific, and Australia	3107.2	195.1	6.3	248.6	8.0
Europe	2010.8	6.7	0.3	72.7	3.6
Latin America	2039.6	60.5	3.0	50.9	2.5
Near East	1801.9	91.5	5.1	14.1	0.8
North America	1923.7	4.6	0.2	14.5	0.8
Total	12781.3	397.1	3.1	434.3	3.4

Source: FAO Soil Portal (www.fao.org/soils...of...soils/salt-affected-soils/...salt-affected-soils/en/)

Table 18.2 Demand and supply of fodder (million Mg) in Rajasthan

Year	Demand	Supply	Gap
1980	61.20	28.50	32.70
1990	58.80	31.52	27.28
1995	67.47	44.70	22.77
2001	72.18	50.08	22.10
2006	76.51	56.08	20.43
2016	84.16	61.60	22.56

Source: Animal Husbandry Department, Rajasthan (Anon 2015)

total area of permanent pastures and grasslands is about 12.4 million ha (Mha) or 3.9% of the country's geographical area. An area of 15.6 Mha, classified as wasteland, is also used for grazing. Forests, and their associated grasslands and fodder trees, are another major source of grazing and fodder collection (Misri 1999). The estimated current and projected requirement and availability/supply of fodder from forest and non-forest areas for Rajasthan are given in Table 18.2.

The animal population growth rate is very high in the state, and the availability of fodder that is already in short supply by nearly 50% is likely to get more aggravated (Anon 2015). The opportunity for increasing the area under cultivated forage is remote due to preferential need of food for human population. Such a situation, therefore, demands full exploitation of the area under cultivated forage and existing pasturelands including salt wastelands.

2 General Features and Management of Salty Soils

2.1 Extent and Distribution

In India, large area suffers from salinity and alkalinity problems, and 6.73 Mha area has been reported to be salt-affected, out of which about 50% (2.98 Mha) occurs in the states of Rajasthan (0.38 Mha), Gujarat (2.22 Mha), and Haryana and Punjab (0.38 Mha) (Table 18.3).

In Rajasthan, the soils with primary soil salinity are encountered in the natural saline depressions like the Pachpadra, Didwana, Sambhar, and few others and cover 2.1% area of the state. Besides these, extraordinary occurrences of these are seen in the far floodplain of river Ghaggar and in part of the Luni basin. However, small pockets of salt-affected soils lie scattered not only in the arid zone but also in the semiarid zone. In IGNP command area of Rajasthan, large stretches have been waterlogged and salinized. Due to seepage about 0.6 m, water is being added daily around to groundwater in the IGNP command area (Tewari et al. 1997).

In case of Gujarat, these are both inland and coastal salt-affected soils and mainly distributed in Kachchh, Patan, Surendranagar, Banaskantha, Jamnagar, Porbandar, Junagarh, Bhavnagar, Ahmedabad, Bharuch, and Surat districts. Sodium chloride is

Table 18.3 Extent and distribution of salt-affected soils in India

S. No.	State	Saline soils (ha)	Alkali soils (ha)	Coastal saline soil (ha)	Total (ha)
1	Andhra Pradesh	0	196,609	77,598	274,207
2	Andaman and Nicobar Islands	0	0	77,000	77,000
3	Bihar	47,301	105,852	0	153,153
4	Gujarat	1,218,255	541,430	462,315	2,222,000
5	Haryana	49,157	183,399	0	232,556
6	Jammu and Kashmir	0	17,500	0	17,500
7	Karnataka	1307	148,136	586	150,029
8	Kerala	0	0	20,000	20,000
9	Maharashtra	177,093	422,670	6996	606,759
10	Madhya Pradesh	0	139,720	0	139,720
11	Orissa	0	0	147,138	147,138
12	Punjab	0	151,717	0	151,717
13	Rajasthan	195,571	179,371	0	374,942
14	Tamil Nadu	0	354,784	13,231	368,015
15	Uttar Pradesh	21,989	1,346,971	0	1,368,960
16	West Bengal	0	0	441,272	441,272
	Total	**1,710,673**	**3,788,159**	**1,246,136**	**6,744,968**

Source: CSSRI (2015) and Sharma et al. (2004)

the dominant salt. The coastal saline area of Gujarat (0.714 Mha), especially Saurashtra and Kachchh, receives lowest rainfall and thus, in the presence of high saline groundwater, presents more serious problems of management. The basic reasons contributing to salinity are (i) lateral ingress of seawater in lower aquifers, (ii) heavy withdrawal of groundwater, (iii) poor natural recharge, and (iv) tidal water ingress in upper aquifers (Nayak et al. 2000). The geo-climatic distribution and characteristics of salt-affected soils in India are summarized in Table 18.4.

2.2 *Classification*

During accumulation of knowledge on the nature, characteristics, and plant growth relationships in salt-affected soils, two main groups of these soils have been distinguished (Szabolcs 1974). These are:

2.2.1 Saline Soil

Soils containing sufficient neutral soluble salts to adversely affect the growth of most crop plants. The soluble salts are chiefly sodium chloride and sodium sulfate. But saline soils also contain appreciable quantities of chlorides and sulfates of calcium and magnesium.

Table 18.4 Geo-climatic distribution and characteristics of salt-affected soils in India

Main traits	Annual rainfall (mm)	Distribution
Alkali soils of Indo-Gangetic alluvial plains. High pH, EC, and ESP and preponderance of $NaHCO_3$ and Na_2CO_3	600–1000	Parts of Punjab, Haryana, Uttar Pradesh, Bihar, Rajasthan, and Jammu region of Jammu and Kashmir
Inland saline soils of arid and semiarid regions. Neutral to alkaline, high EC, and preponderance of Cl^- and SO_4^{2-}	<500	Parts of Haryana, Punjab, Rajasthan, and Uttar Pradesh; Leh, Pulwama, and Patgam districts of Jammu and Kashmir
Inland saline soils of subhumid regions. Neutral to alkaline, high EC, and preponderance of Cl^- and SO_4^{2-}	1000–1400	North Bihar
Inland salt-affected deep black soils (vertisols). Neutral to highly alkaline pH, high EC, and preponderance of Cl^- and SO_4^{2-} with or without HCO_3, montmorillonitic mineralogy	700–1000	Parts of Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Gujarat, and Karnataka
Medium to deep black soils of deltaic and coastal semiarid regions. Neutral pH, high EC, and preponderance of Cl^- and SO_4^{2-} montmorillonitic mineralogy	700–900	Saurashtra coast in Gujarat and deltas of the Godavari and Krishna rivers in Andhra Pradesh
Saline marsh of the Rann of Kachchh. Neutral to slightly alkaline pH, high EC, and preponderance of Cl^- and $SO^{2-}{}_4$	<300	Rann of Kachchh in Gujarat

Source: Sharma (1998)

2.2.2 Sodic Soil

Soils containing sodium salts capable of alkaline hydrolysis, mainly Na_2CO_3, were termed as “alkali” in older literature. Sodic soils contain a high exchangeable sodium percentage (>15%) and high pH value (mostly in the range of 8.5–10). Sodium ions have an adverse effect on plant metabolism and nutrition. Most of the plants cannot tolerate the high pH associated with sodic soils. The high pH leads to low micronutrient availability and decreases the availability of macronutrients such as calcium, magnesium, and phosphorus. Accumulation of elements such as sodium, molybdenum, and boron in plants can result in direct toxicity and may lead to plant injury or reduced growth and eventually death in more sensitive plants. Anions associated with sodicity such as high HCO_3^- are directly toxic to plants (Yadav 1989).

These two main groups of salt-affected soils also require different approaches for their reclamation and utilization. Also, amelioration of the salt-affected soils in the rainfed/arid areas is beset with numerous constraints because of water shortage. The scanty rainfall is the only source of fresh water which should be conserved for raising plantations to improve these soils. Appropriate tree species and planting methods can help rehabilitation of arid salty areas that are characterized by low rainfall, high evapotranspiration demands, highly saline groundwaters, and calcareous subsoils. Keeping these facts in mind, the technology has been developed.

Essential features of the technology are:

- Growing of tolerant species
- Use of amendments
- Planting practices

2.3 Gypsum: The Key Amendment

Gypsum is most commonly used among the various amendments like pyrite, sulfuric acid, and phosphogypsum, because it is very effective, cheap, locally available, and easy to handle. Gypsum ($CaSO_4$. $2H_2O$) of 85% purity ground to 2 mm (ten meshes) is commonly used for agricultural purposes.

2.4 Use of Fertilizers

Work at CSSRI, Karnal suggests that crops on alkali soils generally needs 20–25% more nitrogenous fertilizer than those on normal calcareous soil (Abrol and Gupta 1990). Doddema et al. (1986) reported that ammonium and nitrate decreased in soil and plants in parallel with increasing salinity in a study conducted on the N-metabolism of *Arthrocnemum fruticosum*, growing in a saline area northeast of the Dead Sea in Jordan. Nitrite was only found in the roots and always in very low quantities. In practices for raising *Prosopis juliflora* plantations in saline soils, Singh (1998) reported that application of phosphorus and zinc aids growth in saline soils. Abdel-Hady (2007) reported that N, P, and K concentrations and their uptake of barley plants increased by increasing Zn application. Sodium concentration of tissues decreased with increasing Zn rate and its uptake. Zn content of the fresh and dry weight increased with increasing Zn rate at different salinity level as compared with control. Gobarah et al. (2006) reported that foliar spraying with zinc levels had a significant effect on groundnut growth, yield, and its components as well as seed quality. Arya et al. (2005) reported that treatments positively influenced the growth of *S. persica*, and application of nitrogen in combination with gypsum gave better results as compared to application of nitrogen only. Treatments with gypsum + 9g N was the best attaining 207 cm of height and 212 cm of crown diameter, which was 38 and 24% more than the untreated plants producing 12 kg per tree of aboveground fresh biomass, which was 71% more than the control. Rao et al. (2004) reported that application of ammonium sulfate with saline water irrigation at the time of fruiting enhanced the oil yield in *S. persica*. Thus, with proper nutrient management, growth and yield may be enhanced on salt-affected soils.

2.5 Salt-tolerant Plant Species

Studies on techniques of amelioration, raising plantations, and choice of species have been undertaken in our country and other countries as well. These were reviewed under different headings earlier also (Yadav 1980; Manchanda et al. 1989; Yadav and Prakash 1990; Dagar 2003). Research on many aspects of afforestation is conducted in semiarid region by the Central Soil Salinity Research Institute, Karnal (Dagar et al. 2001; Singh and Dagar 2005; Dagar 2014).*Prosopis juliflra-Leptochloa fusca* silvopastoral model was found to be excellent for fuelwood and forage production and for the amelioration of high pH soils. This system, when followed for little more than 4 years, reclaims alkali soils to such an extent that normal agriculture crops such as *Trifolium alexandrinum* and *T. resupinatum* can be grown successfully (Dagar 2009, 2014).

Based on a series of long-term experiments, *L. fusca* was rated as the most tolerant grass on highly alkali soil and waterlogged conditions. Also in a silvopastoral experiment, *Acacia nilotica*, *Eucalyptus tereticornis*, and *Parkinsonia aculeata* were planted on ridges, and kallar grass (*L. fusca*) was established in trenches between ridges successfully (Dagar 2009). However, literature is scanty regarding grasses or silvopastoral system on arid salt-affected soils. Arya et al. (2005) reported improvement in soil properties of highly saline soil in arid Rajasthan due to afforestation activities which promoted colonization, and the number of plant species (mostly salt-tolerant grasses) increased gradually. In the same field, *Cenchrus setigerus* (a highly palatable non-salt-tolerant grass) was established on soil structures (Arya et al. 2011) with 1.1 kg m^{-2} green yield on slope after 10 years of plantation activities.

In a study conducted in sodic soils of semiarid region in Haryana, India (Singh et al. 1989), *Prosopis juliflora* produced positive results of gypsum application on survival. The amelioration of original salty soil with amendments (gypsum at 50% GR and 24 kg FYM) was reported to give superior growth, avoiding the need to replace the soil in planting pit (Yadav et al.1975). Arya et al. (2005) reported that soil amendment with gypsum at 100% GR and 3 kg FYM gave very encouraging growth equivalent to that obtained using the amendments applied in the auger hole technique (Gill et al. 1993). Although *Acacia ampliceps* grew well under saline environment, its maximum growth was observed under low to medium salinity patches (4–12 dS m^{-1}) showing survival percentage of 80–90. However, at higher salinity (12–16 dS m^{-1}), the percent survival of *A. ampliceps* was 50 (Ashraf et al. 2006). Results from Auroville, Pondicherry, India, showed that *A. ampliceps* survived and grew very well at highly saline eroded black soil wasteland and gave sufficient biomass (Auroville 2001).

Although sensitive to waterlogging, most *Atriplex* species grow well in saline soils between ECe 20 and 30 dS m^{-1} without any significant impact on growth; while *A. halimus* and *A. canescens* tend to be the most palatable, prolific, and salt-tolerant, *A. nummularia* and *A. amnicola* are known for their extreme drought resistance. Most *Atriplex* species contain 12–22% leaf protein content, regenerate well after grazing, and can survive at salinity levels up to 30–35 dS m^{-1} with minimal yearly rainfall. *A. barclayana*, easily propagated from cuttings, can be irrigated with seawater and is known for its high biomass production. *A. undulata* is currently being cultivated and harvested by large-scale commercial fodder operations in Australia. Many *Atriplex* species (over 400) perform well under saline conditions and provide for an excellent forage compliment when interplanted with native vegetation. *A. nummularia* grows well with only 150–200 mm annual rainfall. Native stands of *Atriplex* produce about 0.5–4 Mg of dry matter per hectare per year. When grown with irrigation, yields equivalent to those of conventional irrigated forage crops can be obtained (Runciman and Malcolm 1989).

Pasture with a mixed population of *A. canescens* and native vegetation sustained three sheep per hectare with 250 mm annual rainfall. *A canescens* is also palatable to cattle. In Israel and North Africa, a Mediterranean species, *A. halimus*, has proven hardier than *A. nummularia* or *A. canescens*. Although less palatable, it will grow in shallow soil and on slopes where other plants cannot survive. It does well with a winter rainfall of 200 mm but should be interplanted with more palatable species (Barrett-Lennard and Malcolm 1995). In research trials conducted by AFRI, Jodhpur (India), 2.6 Mg ha^{-1} of biomass was produced from *A. lentiformis* with gypsum, FYM, $ZnSO_4$, urea, and drainage (Arya et al. 1998).

2.6 Medicinal Plants

Some of the aromatic crops, viz., palmarosa (*Cymbopogon martinii*), lemongrass (*C. flexuosus*), vetiver (*Vetiveria zizanioides*), and German chamomile (*Matricaria chamomilla*), and medicinal crops like periwinkle (*Catharanthus roseus*), ergot (*Claviceps purpurea*), Egyptian henbane (*Hyoscyamus muticus*), and isabgol (*Plantago ovata*) have been found promising for cultivation under salt-affected conditions (Dagar 2014). In most of the crops, essential oil yield and quality of oil and content of principal ingredients in medicinal plants are not affected by salinity or alkalinity (Patra and Singh 1995; Anwar et al. 2001; Cedmap 2001). Tewari et al. (2001) reported that *Phyllanthus amarus* is found to be well adapted to variety of soils (at soil pH ranging from alkaline to neutral and acidic conditions) and shown preference for calcareous well-drained and light-textured soil. Singh et al. (2004) also reported steady increase in available N status as compared to initial level after cultivation of aromatic crops palmarosa (*Cymbopogon martinii*), lemongrass (*Cymbopogon flexuosus*), and citronella java (*Cymbopogon winterianus*) with and without amendments (sludge, hyacinth compost, and pyrite) alone and in combination with organic and inorganic amendments in saline-sodic soil. Dagar (2003) and Dagar and Singh (2007) reported 1140 vascular salt-tolerant plants (including medicinal and coastal) found in India, about thousands of them are reported to be used for different purposes.

2.7 Improvement in Soil Properties

Bhojvaid et al. (1996) reported that in a study carried out on the soils collected under *P. juliflora* plantations of different age, the afforestation improved physical and chemical properties of surface soils by decreasing pH, electrical conductivity, and exchangeable Na levels and increasing infiltration capacity, organic C, total N, available P, and exchangeable Ca, Mg, and K levels. The amelioration effect of the trees on top soil increased with duration of tree occupancy. Soil nutrient status under the 30-year-old plantation was higher than that of the non-sodic farm soil.

Arya et al. (2005) reported that in general organic carbon values increased over the initial values, which may be ascribed to the fact that the *Salvadora persica* plantation provided better root environments for the growth of other plants such as grasses and herbs. Water was captured and conserved as groundwater, instead of being lost through evaporation and runoff. The extensive roots of the different species opened the soil, increasing air exchange, organic matter, and hydraulic conductivity, and the decreased rhizosphere pH resulting from root exudates stimulated biological activity and released plant nutrients. Foliage deposition on the soil also increased organic matter, humus, and mulching, decreased evaporation, and improved the physical properties of the soil. Thus, over time the degraded salt-affected lands improve. Field studies elsewhere on other plant species (Hollington et al. 2001; Singh et al. 1989; Tiedemann and Clemmedson 1986) also found that soil under plant canopies contain two to three times more organic matter.

3 Work Done at Arid Forest Research Institute, Jodhpur (Case Studies)

3.1 Site Conditions

3.1.1 Rajasthan

The study area is located near Gangani village in Jodhpur district of arid Rajasthan. This part is characterized by sandy plain having hard and compact substrata at shallow depth, which is impervious to roots and water (Anon 1999). The soil of the experimental site was classified as lithic, calcid, coarse sandy to loamy sandy soil. The soil of the experiment area was shallow (25 cm) underlain with a thick hard pan of calcium carbonate. The soil pH was ranging from 8.8 to 9.8 while EC from 4.2 to 16 dS m^{-1}. The salt encrustation was observed at many places with EC value as high as 48 dS m^{-1}. The exchangeable sodium ranged from 30 to 60%. The soil gypsum requirement was found to be 6 Mg ha^{-1}. The organic carbon contents ranged from 0.1 to 0.2%. Soil was poor in nitrogen and phosphorus. The mean annual rainfall of the site is 350 mm, which is mainly confined to the monsoon period (from July to

September). The total number of rainy days during the year varies between 8 and 17 days. The maximum temperature rises as high as 50°C in summer and minimum drops to 4°C in winter. Average wind velocity in the summer months is recorded as 20–30 km h^{-1}.

3.1.2 Gujarat

Kachchh is the largest district of Gujarat state with an area of 45,652 km^2 of which 5675 km^2 is naturally salt-affected (12.7%), the saline Rann 17, 215 km^2 (37.6%), and mud flats occupy 3,397 km^2 (7.4%). The experimental area is located in Kordha, Sami Range in Patan (23.83°N latitude 72.12°E longitude) of Gujarat, India. The area is on the fringe of Little Rann of Kachchh. The soil of the area are highly saline silty clay-textured black soil (medium) having soil depth ranging from 40 to 100 cm.

3.2 Species Tried

3.2.1 Halophytes

These are generally defined as plants (i.e., grasses, succulents, herbs, shrubs, and trees) that grow in a wide variety of saline habitats from coastal sand dunes, salt marshes, and mud flats to inland deserts, salt flats, and steppes. *Atriplex lentiformis* and *A. amnicola* (exotic) and *A. stocksii* (indigenous – Gujarat) shrubs of genus *Atriplex*, popularly known as saltbushes, are salt excluders; the leaves accumulate salt in the cell vacuoles and in bladder cells. The bladder cell can release their salts during rains, making the foliage palatable to sheep after the rainy season.

Suaeda nudiflora (*Unt Morad* – Gujarat) is a succulent halophyte. The large central vacuole in the thin-walled cell of these watery leaves and stems accumulates substantial quantities of salts. Thus, the toxicity is partitioned from the cytoplasm and organelles of the cells. Salts are removed from the plant when the leaf is shed (Shah 1978).

Salvadora persica (*Khara Jal*) – an evergreen multipurpose tree, belonging to family Salvadoraceae, is the main salt-tolerant indigenous tree species on arid salt-affected lands in India, particularly in Rajasthan, Gujarat, Punjab, and Western Uttar Pradesh. It is a preferential halophyte that stores excess salts in mature and senescent leaves and in the bark which, when shed, remove excess salts (Amonkar and Karmakar 1978). *S. oleoides* is also quite common in dryland conditions of Rajasthan and Gujarat.

3.2.2 Glycophytes

Acacia ampliceps (salt wattle) belonging to family Mimosaceae, is native to south-western Australia, is a shrub or small tree 2–8 m high, can be found on sandy or loamy alluvial soils with an alkaline reaction, and is highly tolerant to salinity (Aswathappa et al. 1987).

A. colei (Cole's wattle) is widespread in inland northern Australia. This fast-growing, short-lived, nitrogen-fixing shrub or small tree reaches heights of up to 9 m. The soils are typically neutral but range from slightly acidic to alkaline (Aswathappa et al. 1987).

Azadirachta indica (*neem*) belonging to family Meliaceae, is a small- to medium-sized tree, with a short and straight bole. It grows on most kinds of soil: black cotton soil, compact clays or lateritic crusts, moderately alkaline soil, stony or hard calcareous pan shallow soil, and well-drained loam soil. It does not grow well on waterlogged sites and silty sands and almost fail to grow on silty flats and in clayey depressions with impeded soil aeration and percolation (Troup 1981).

Colophospermum mopane (family: Fabaceae) is a shrub to tall tree that grows in hot, dry, low-lying areas up to an altitude of 200–1150 m in the far northern parts of South Africa and in Zimbabwe, Mozambique, Botswana, Zambia, Namibia, Angola, and Malawi. It is found growing in alkaline (high lime content) soils which are shallow and not well drained (Lock 1989). It has been introduced in India also by CAZRI Jodhpur and is performing well.

3.3 *Planting Practices*

3.3.1 ***Pit Planting*: *In Deep Soils (40cm–1m Depth)***

Pits of 50 cm × 50 cm × 50 cm were dug, and 3 kg farmyard manure (FYM), 15 g single super phosphate (SSP), and gypsum (according to treatment) were mixed with pit soil at the time of planting. The FYM contained 33–34% carbon and 0.7–1% nitrogen, giving nearly 1 kg carbon and 3 g nitrogen to every plant. Soil drenching with 0.2% chlorpyrifos was also carried out. Crescent-shaped drainage trenches of 130 cm × 30 cm × 30 cm were made around individual plant along the slope to facilitate the leaching of salts.

3.3.2 ***Mounds*: *In Shallow Soils (20–40 cm Depth)***

Double-ridge mound (DRM) was adopted from the studies carried out in Australia (Ritson and Pettit 1992), while circular dish mound (CDM) was developed based on our field experience. For making double-ridge mounds, bunds (0.50 m broad and

0.45 m high) were constructed with the help of a tractor and ridges (20 cm high) were made manually. The distance between two ridges (planting space) was 1.2 m. CDM were prepared by raising soil to a height of 20 cm in a circle of 2.0 m diameter manually.

3.4 Amendments Used

In Rajasthan–	Farmyard manure (FYM), gypsum, and nitrogen (urea and calcium ammonium nitrate)
In Gujarat–	FYM, wheat husk, pearl millet (*Pennisetum typhoides*) husk, and urea

3.5 Mulching

Mulching from locally available grass (*Sporobolus diander*) was applied.

3.6 Results

3.6.1 Shrubs

3.6.1.1 *Atriplex* spp.

Exotic shrubs of genus *Atriplex* performed well on arid saline-alkali lands with FYM and nitrogen. Trial of *Atriplex lentiformis* was laid in 1997 with three levels of gypsum (0–150%) and six nitrogen levels (0–100 g urea). Crescent-shaped drainage trenches were made around individual plant along the slope to facilitate the leaching of salts. Survival ranged from 45 to 83% in different treatments; 5.5 years after planting, gypsum-treated bushes recorded higher survival. It responded to nitrogen application and maximum growth, and biomass was recorded in treatments where 60 g of urea was applied with different levels of gypsum at 14 months of age. Nitrogen doses increased the leaf component. Mean percent allocation showed that percent leaf component was lowest in treatment without nitrogen (Arya and Tewari 2009; Arya 2013).

On double-ridge mound (DRM), 100% gypsum-treated bushes recorded maximum survival of 97% followed by 89% for 50% gypsum and 88% for control at 20 months of age. Calcium ammonium nitrate-treated bushes recorded better survival as compared to urea-treated bushes with or without gypsum application. Application of nitrogen increased the growth. CAN was found to be better source of

Table 18.5 Performance of various *Atriplex* species on soil structures at 36 months of age on degraded salty soil at Gangani, Jodhpur (India)

	A. stocksii			*A. lentiformis*			*A. amnicola*		
Parameters	DRM	CDM	Control	DRM	CDM	Control	DRM	SRM	Bund
Survival (%)	87.5	50	21	66.7	95.7	21	91.6	86.1	94.4
Height (cm)	45.7	47.3	40.8	80.1	84.8	41.1	76.4	61.9	71.1
Crown dia. (cm)	59.6	91	68	110.0	113.6	82.2	116.4	96.9	109.2
Leaf biomass (g shrub^{-1})	1366.7	956.7	475.0	1825.0	2316.7	375.0	600.0	630.0	740.0
Branch biomass (g shrub^{-1})	991.7	591.7	263.3	1444.7	1175.0	253.3	1300.0	710.0	1320.0
Total biomass (g shrub^{-1})	2358.4	1548.4	738.3	3269.6	3491.7	628.3	1900.0	1340.0	2060.0

DRM double-ridge mound; *CDM* circular dish mound

nitrogen than urea. A maximum average height of 89 cm and crown diameter of 158 cm was in treatment: [(100% soil G.R + 9 g of N (CAN)]. The green biomass yield was ranging from 1 Mg ha^{-1} to 3.2 Mg ha^{-1} in different treatments (Arya and Tewari 2009). Double-ridge mound for *A. stocksii* and circular dish mound for *A. lentiformis* enhanced the survival, growth, and biomass production. Overall, *A. lentiformis* recorded significantly more mean green biomass (2462.2 g) compared to 1548.3 g for *A. stocksii* (Table 18.5). Root development was alongside the ridges in DRM, while in CDM root development was in all direction along the circular dish mound with occasional root going out of the soil structure. Overall CDM was the best structure, and it produced 562.5 and 256.0 g shrub^{-1} fresh and dry root mass which was 2.8 and 15.0 and 2.1 and 12.2 times more than DRM and control, respectively (Arya 2009).

A. amnicola bushes maintained appreciably high survival; after 72 months, DRM maintained 73.6%, while SRM and bund both recorded 70.8% survival. Gypsum application was not influencing the height and crown diameter at any stage of growth up to 36 months of age. Structures very significantly (p-0.00) influenced the total yield. Total biomass yield (green) was maximum on bund (2.05 kg bush^{-1}) followed by DRM (1.92 kg bush^{-1}) and SRM (1.11 kg bush^{-1}) at 36 months (Table 18.5). Bushes have regrowth potential, produced viable seed, and did not suppress the native vegetation. The study showed that it has very good potential to produce nitrogen-rich fodder on very highly degraded shallow saline-alkali soil with minimum management (Arya et al. 2010).

All the three shrubs were tried in Gujarat also, but the soil was very shallow and degraded. They survived for 1 year but did not survive under the hot and drought conditions in 2009.

3.6.2 Tree Species

3.6.2.1 Rajasthan

3.6.2.1.1 Salvadora persica

Survival of *S. persica* ranged from 67 to 85%, despite deficient rainfall, including a severe drought, in different treatments after 72 months. Treatments positively influenced the growth and application of nitrogen in combination with gypsum which gave better results as compared to application of nitrogen only. T_6 with gypsum + 9g N was the best treatment, attaining 207 cm of height and 212 cm of crown diameter, which was 38 and 24% more than the untreated plants, and producing 12 kg tree^{-1} of aboveground fresh biomass, which was 71% more than the control (Arya and Lohara 2005). Crescent-shaped drainage trenches for individual plants helped in plant establishment and growth, serving the dual purpose of harvesting water and leaching salts (Arya et al. 2005, 2014).

3.6.2.1.2 Acacia ampliceps

It performs very well on deep alkali soils (soil depth 60–75 cm min). It recorded overall 55.4% survival for control and 65% for gypsum-treated trees on deeper soil (60–75 cm depth) as compared to 45% for control and 35.2% for gypsum-treated trees on shallow soil area (25–40cm depth) at 72 months of age. Gypsum application enhanced the growth and yielded a twofold biomass (12 kg tree^{-1}–5.43 kg tree^{-1} for gypsum treated and 8.1 kg tree^{-1}–3.9 kg tree^{-1} for untreated trees on deeper and shallow soils) at the age of 5 years. Roots were excavated at great depths; they penetrated more (1.56 m) in the deeper soil compared to shallow soil (0.56 m) where their horizontal spread was more. The mean root mass (1.7–1.1 kg tree^{-1}) and root volume (915–638 cc) were significantly higher in deeper soil; however, a number of roots (14.5–8) and total root length (961–889 cm) were significantly higher for shallow soil. It was due to the presence of indurate nodulated $CaCO_3$ layer root which could not penetrate deep enough and has a spreading system to fulfill the need for nutrition and moisture. Flowering was recorded in 60% of plants at 3 years of age (Arya 2014).

3.6.2.1.3 Suaeda nudiflora

It is a perennial shrub species found on mud flats along the sea coast or in saline soils in Gujarat and used as fodder. It recorded nearly 100% survival and attained maximum growth. It produced maximum total dry biomass on all the three structures, 2.16 Mg ha^{-1} on DRM, 2.25 Mg ha^{-1} on CDM, and 1.09 Mg ha^{-1} on control (Arya and Lohara 2006; Arya 2009). At 72 months, *S. nudiflora* recorded 79.2 and 66.7% survival on CDM and DRM as compared to 55% under control conditions. No well-defined taproot was observed. Roots penetrated the *kankar* pan (hard calcareous layer in soil) in DRM, partially in CDM but not in control (Arya et al. 2006).

3.6.2.1.4 Azadirachta indica

A trial with two tree species, *Acacia colei* and *Azadirachta indica*, was laid with three treatments of planting in August 2001. *A. colei* failed to survive the experimental conditions attaining less survival and very poor growth. Its root system was fibrous and shallow resulting in poor growth. It is reported also that *A. colei* has an extensive shallow root system and is severely stressed when planted too close. The closely planted *A. colei* fails to grow or set seed. The current planting distances recommended for Nigeria is 10 m apart. It may be more suited in the semiarid conditions. Results also suggest that *A. indica* has the potential to grow on arid saline-alkali site but unable to cope with dual stress of salinity and drought. Supplemental irrigations from normal water will give better results (Arya and Lohara 2008).

3.6.2.1.5 Colophospermum mopane

It maintained 89% overall mean survival after 5 years of establishment (86.5% in control and 92.1% on CDM) on salty wastelands. Plants on CDM structure attained 113 and 158 cm as mean height and crown diameter, respectively, as compared to 101 and 151 cm for control at 60 months of age. Overall, plants on CDM recorded a mean 1.45 kg green biomass yield plant^{-1} which is 5.9% more compared to plants grown under control (1.37 kg); the difference was 9.1% for leaf and 5.2% for branch component, respectively. Its roots penetrated the $CaCO_3$ nodulated *kankar* pan further enhancing its utility. The mean fresh root mass was 32% higher under control conditions (729.1 g per tree) compared to CDM structure (552.5 g per tree). However, the mean root length (823 cm) and root numbers (15) were the same for both structures. It did not suppress the growth of indigenous salt-tolerant grasses, mainly *Sporobolus* spp. and *Chloris* spp. It adapted well, flowered, and produced viable seed. Natural germination is also observed through the seed (Arya and Lohara 2016).

3.6.2.2 Gujarat

3.6.2.2.1 Salvadora persica

It proved to be the best plant facing the extemely harsh conditions of high salinity, heat stress after two consecutive summers (2009 and 2010) and one drought year (2009), and eratic monsoon afterwards. It showed no effect of heat shock. It recorded 91.6% mean survival after 48 months. All the treatments recorded significantly ($p \leq 0.05$) higher green biomass yield as compared to control (2.60 kg plant^{-1}). Application of urea and FYM gave the highest biomass (7.13 kg tree^{-1}) which is significantly higher than all other treatments. It flowered and produced fruits in the second year. It influenced the soil properties also. Soil pH was significantly decreased in side plant pit; however, soil EC increased from initial values (1.32–2.72 dS m^{-1} and 1.75–2.71 dS m^{-1}, in 0–25 cm and 25–50 cm soil layers, respectively) but was in normal range; salt content in leaf may be responsible with no effect in inter-row spaces. Percent soil organic carbon also registered an increase from 0.12 to 0.23% and 0.10 to 0.24% in 0–25 cm and 25–50 cm soil layers, respectively.

3.6.2.2.2 Acacia bivenosa

A. bivenosa was at the second place, surviving one summer and one drought year with 10.2% decrease in mean survival, 77.3% at 30 months compared to 12 months (86.1%). Despite all the adversities, it maintained 40.5% mean survival, after 48 months of establishment. It has a shrubby nature. It responded to treatments applied and positively influenced the survival, growth, and biomass yield. Application of FYM and wheat husk resulted in 66.1 and 62.8% survival. All the treatments recorded higher biomass as compared to control (3.43 kg) at 36 months of age. A maximum 12.68 kg $tree^{-1}$ biomass yield was obtained for wheat straw treatment followed by 10.22 kg $tree^{-1}$ for FYM treatment.

3.6.2.2.3 Acacia ampliceps

It is the most fast-growing species and displayed a shrubby nature. It maintained appreciably high mean survival of 72.6% up to 18 months. Plantation suffered with heat shock in May 09. In general, causalities were high in shallow soil depth for both the *Acacia* spp. After the deficient monsoon and second successive hot summer, mean survival was further reduced to only 12.7% at 36 months, ranging from 06.0% in control to 18.7% with wheat husk treatment. Some of the surviving trees attained good growth. The biomass yield is highest among all the three species tried. The yield was ranging from 5.5 kg $tree^{-1}$ in treatment FYM + wheat husk to 13.01 kg $tree^{-1}$ in urea and FYM treatment (Arya et al. 2010). Both the acacias flowered and produced viable seed within 2 years. Resprouting was observed 100% in plants cut for aboveground biomass estimation. However due to moisture deficiency, it did not grow further. Natural germination through the seed was also observed. Their growth improved the soil conditions, decreased pH and ECe, and increased organic carbon.

4 Conclusions

Halophytes performed better than glycophytes in salt-affected soils. *Salvadora persica* and *Suaeda nudiflora* were the best species among the indigenous plant species, while *Acacia ampliceps*, *A. bivenosa*, and *Colophospermum mopane* were the best exotic species. Shrubs of genus *Atriplex* have the potential to produce nitrogen-rich fodder from highly degraded arid salt-affected soils. High ash content (~40%) requires its mixing with cereal residues.

Large pit size is necessary to mix amendments to create less salty environment during seedling establishment on sandy calcareous salty soils. Double-ridge and circular dish mounds enhanced survival of all the plant species by providing protection from waterlogging and less salty environment. Crescent-shaped drainage trenches served the dual purpose – helped in leaching of salts and harvesting of water. On black silty soil, mixing of wheat husk and FYM with pit soil enhanced the growth significantly.

Improvement in soil status, substantial reduction in soil pH and electrical conductivity and improvement in percent organic carbon content during the study period, is observed. Plantation activities promoted the natural regeneration, and a number of plant species increased gradually. Green biomass yield of associated species was 762 g m^{-2} (in 2000), 768 g m^{-2} (in 2001), 58 g m^{-2} (in 2002), and 620 g m^{-2} (in the year 2003), respectively, on sandy salty soil of Jodhpur (6 years after the establishment of plantations).

5 Gaps and Further Research Needs

Production from nonproductive salt-affected soils is necessary to cater the food, forage, timber, fuelwood, oil-seed, medicine, and other minor product demands of the ever-increasing human and cattle population. Since water is the most limiting factor in reclaiming these wastelands, intensive research on water harvesting and use of saline/sodic water is needed. Research should also focus on search for locally available cheaper amendments to lower the cost of reclamation. Many halophytes produce high biomass with minimum management from the soils with high level of management that even commercial forestry is feasible. Arid zone economy is livestock based, but due to the increasing human pressure, even marginal lands are used for agriculture. Adopting biosaline agroforestry, the nomadic behavior of large population may be checked in dry regions (Yadav 2006).

Researches to use genetic engineering for production of salt-tolerant transgenic crops need to be encouraged. However, to avoid reversion of soil sodicity/alkalinity and to ensure sustainability of reclamation technology, proper post-reclamation managements are extremely essential. Changes in soil properties should be periodically monitored to facilitate timely corrective measures. Time-bound, well-planned, and adequately supported action program with active support from the government will result in profitable rehabilitation and sustainable management of salt-affected soils in the country, thereby promoting food security, environment safety, and national prosperity.

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Chapter 19
Performance of Some Agroforestry Trees in Reclamation of Salt-affected Soils in the Lowlands of Ethiopia

Hadia Seid and Emiru Birhane

Abstract To determine the performance of some agroforestry trees in the reclamation of salt-affected soils in the lowlands of Ethiopia, we studied the effects of a series of soils with differing levels of salinity on three indigenous tree species, *Balanites aegyptiaca, Tamarindus indica*, and *Acacia tortilis*. We found that salinity had a significant effect on seedling performance. Increasing the soil salt levels caused a significant reduction in the height and in the dry stem and dry root weights of the three species tested. Based on seedling growth parameters, *B. aegyptiaca* was salt-tolerant even at a high level of salinity (12 dS m^{-1}), while *T. indica* was moderately salt-tolerant. Salinity had a significant effect on soil compared with control soil in the trees' response to soil chemical properties. At the seedling stage, *B. aegyptiaca* and *T. indica* were found to be the most efficient salt cleansers compared with *A. tortilis*. Salinity and the interaction between species and salinity level had a significant effect on all seedling growth parameters and soil chemical properties, indicating that salinity was a limiting factor for plant growth. Salinity had a significant effect on the productivity index. *A. tortilis* and *B. aegyptiaca* contributed more to soil productivity improvement than *T. indica*. Further, at the top (0–50 cm) soil depth, the base of the trees had a higher soil productivity index than other soil radii. *A. tortilis* was found to be the most salt-tolerant and this species showed the most potential for the improvement of soil productivity, followed by *B. aegyptiaca* and *T. indica.* Therefore, we suggest that *A. tortilis* and *B. aegyptiaca* are suitable for reclamation in arid and semi-arid areas where salinity affects crop development, in both agroforestry systems and strip tree plantings.

Keywords Salt-affected soils · Productivity index · Salt-tolerant · Reclamation · Seedling performance · Furrow irrigation

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1 Introduction

The lowland region in Ethiopia predominantly consists of salt-affected soils; usually soils in this region are dry for a long period throughout the year. This hinders the leaching of soluble salt from the shallow water table area above the critical level (1.5 m), an effect which is attributed to the rising of saline water and related salt problems, resulting from poor water management in irrigation areas that has increased the rate of salinization in the region (Girma and Fantaw 1996).

Regions with an arid climate require large volumes of irrigation water to obtain profitable harvests. The resultant increase in soil salinity reduces harvests and narrows the range of viable crops. Many changes in soil salinity are due to human factors such as soil management, crop choice, irrigation amounts and scheduling, the design and maintenance of drainage networks, the composition of the irrigation water, and the type of application. For instance, in the Amibara Irrigation Project in the Middle and Lower Awash Basins in Ethiopia, about 10,285 ha of land was subjected to a gravity irrigation system, with the two main irrigation methods being basin and furrow irrigation. At present, 40% of the total land is out of production because of its salinity and alkalinity (Girma and Fantaw 1996). Moreover, owing to increasing irrigation needs in these areas, farmers, as well as state and private investors, have removed deep-rooted trees, shrubs, and other perennials and replaced them with shallow-rooted crops. As a result, the salt water has risen to the soil surface by capillary action and the topsoil has become less productive.

One approach to mitigate the salinization problem, achieve sustainable soil quality, and improve crop production could be to introduce and maintain salt-tolerant tree species. Such species promote soil permeability, keep the underground salty water at a lower depth by virtue of natural biodrainage, and reduce some of the negative effects of soil salinity and alkalinity. Against this background, in this chapter we discuss the salt-tolerant levels of three indigenous tree species that are popular among farmers in the lowland region of Ethiopia. By adopting systematic maintenance of such natural vegetation, in the form of farm forestry or along agricultural field boundaries in the form of agroforestry systems, the productivity of salt-affected soil can be maintained to sustain crop production.

2 Irrigation in the Lowlands of Ethiopia

2.1 Irrigation in the Amibara Central Awash Area: Opportunities and Challenges

In Amibara, both private investors and state farms operate commercial irrigated agriculture schemes. The potential for large-scale irrigation development in the Amibara area was first considered in 1964. The first areas of development were irrigated in 1980 and gradually the area was expanded to reach full-scale production, in 1984. The main crops produced are cotton and banana, with limited areas of pasture, cereals, and vegetables. The two main irrigation methods are the basin and furrow methods, for banana and cotton fields, respectively. The project makes an important contribution to Ethiopa's economy through import substitution and foreign exchange earnings. The current production of cotton ranges from 4500 to 7200 Mg of cotton lint, 9000 to 120,000 Mg of cotton oilseed, and 300 Mg of cotton planting seed per year (Tenalem 2007).

Salt-affected soils in the Middle Awash Valley have been a challenge to agricultural production. Five to eight years after the irrigation project commenced, salinity became very severe (Girma and Fantaw 1996), and many productive agricultural lands became sterile and were abandoned. To understand the nature and extent of these salt-affected soils, a salinity study was carried out on 4000 ha (Girma and Fantaw 1996). The results showed that the main cause of salinity was poor irrigation water management and a shallow saline groundwater table. However, there are several natural saline seeps in the region, which can also contribute to salinization (Girma and Fantaw 1996).

Accumulation of salts was high in the surface soil, owing to capillary rise during the fallow season, which resulted in secondary salinization. High free evaporation of water from the surface exacerbated the salinization process in the Amibara Irrigation Project. Saline and saline-sodic soils were the major salt-affected soils in the area. Most of the salts in these soils are easily soluble. While sodium was in excess in saline-sodic soils, calcium was in excess in saline soils. Chloride was the dominant anion in salt-affected soils. Groundwater depth was increased during the rainy months (July–September), and both groundwater salinity and irrigation water salinity were lower during this season (Girma and Fantaw 1996).

3 Managing Salinity and Sodicity Through Tree Plantations

In most arid and semi-arid regions where precipitation is insufficient to leach salt from the root zone, the accumulation of excessive amounts of soluble salts in the root zone is a major limiting factor in crop production and/or management. The only practical way to correct excess soil salinity is to leach and remove the soluble salts from the root zone by periodically applying large amounts of water to the soil. The excess water dissolves the accumulated soluble salts and carries them below the root-zone. This is possible only if the soil internal drainage is adequate. Shallow soils overlying rock, hard clay, or clay pan restrict water percolation and drainage. Breaking through this layer can improve drainage and the downward movement of salts. In the absence of adequate internal drainage, the installation of drain tiles to remove the excess water, along with the dissolved salts, may be the only solution to the problem. However, management of salt-affected soil by leaching and the addition of chemicals incurs higher costs. The availability of alternative cheap and effective technologies will significantly improve the prospects of removing salts from the soil (Tariqul 2009).

However, it should be stressed that there are no modifications or soil conditioners that can remove salts from the root zone or make the salts less harmful. The selection of salt-tolerant turf grass species, good irrigation practices, and adequate drainage are the main practical factors that ensure the successful management of turf grasses under saline conditions (Beard 1973).

The mechanism of sodic soil reclamation by trees involves the dissolving of native calcium carbonate by the biological activity of the tree, the presence of grass roots, the addition of leaf litter, and the turnover of old roots, all of which increase organic carbon (OC) in the soil and water penetration into the soil. The free Ca ions in the soil solution replace the Na ions on the exchange; this initiates biological activity in the soil, with subsequent improvement of organic matter content, moisture, and the fertility regime (Tariqul 2009). However, the degree of reclamation depends upon the kind of tree species, planting density, the management practices that are adopted, and the fencing provided to the plantation to prevent encroachment by humans and animals. Several salt-tolerant forest and fruit species that can be grown in highly sodic and saline soils have been identified. These promising forest species include *Prosopis juliflora, Acacia nilotica, Tamarix articulata*, and *Casuarina equisetifolia* (Tariqul 2009).

3.1 Natural Vegetation in the Amibara Irrigation Scheme Area and Important Agroforestry Trees

Most of the area along the Awash river bank was predominantly covered by *A. nilotica, A. seyal, A. oerfota, A. tortilis, A. mellifera, Salvadora persica, Balanites aegyptiaca,* and *Dobera glabra*, but far away from the river bank most of the area was covered with scattered small-sized A*cacia,* and bush and scrub of different species. At present, significant areas of the district are covered with *P. juliflora* (Shiferaw et al. 2004).

In the Afar tradition, until a few years ago, pastoralists considered it a bad idea to cut any part of a live tree, either for their animals or for other domestic purposes (firewood, fencing, construction, local timber-getting, etc.) (Diress et al. 2007). For instance, the pastoralists assumed that cutting any part of a tree would cause bad drought in the area. However, these days, such management practices are being eroded, owing to overgrazing, caused by increased pressure on the rangelands, increased expansion of settlements, and reduced mobility, factors that exacerbate overgrazing owing to long periods of grazing in few localities (Diress et al. 2007).

To elucidate the performance of some agroforestry trees in the reclamation of salt-affected soils in the lowlands of Ethiopia, we studied the effects of a series of soils with differing levels of salinity on three indigenous tree species, *Balanites aegyptiaca, Tamarindus indica* and *Acacia tortilis*.

3.1.1 *Balanites aegyptiaca* (Azene 2007)

3.1.1.1 Taxonomy and Description

Balanites aegyptiaca belongs to the family Balanitaceae. The tree is native to much of Africa and part of the Middle East. There are many common names for the plant; in English it is called the desert date. In Ethiopia, it has different vernacular names; for example, in Afargna *uddayto*; in Amharic *bedeno, jamo*, and *kudkuda*; in Oromigna *bedena and baddano*; and in Tigrigna *indrur* (Azene 2007). It is a small evergreen tree about 10 m in height, with its crown rounded in a tangled mass of thorny branches (Fig. 19.1). The bark is smooth and green; at a later stage it is dark, cracked, and corky. The tree has 8-cm-length thorns, which are soft at first, then woody. The leaves are arranged in distinctive pairs of gray-green leaflets, and are ovate. The flowers are yellow-green and fragrant and occur in clusters. The fruits are oblong, up to 5 cm in length, with both ends round, yellow when ripe; the seed within is hard and pointed, surrounded by yellow-brown bitter flesh; the seed is easily separated.

Fig. 19.1 Morphology of *Balanites aegyptiaca* (Azene 2007)

3.1.1.2 Ecology

B. aegyptiaca is an important tree found in Asia and all over Africa, from arid and semi-arid regions to sub-humid savannah. In Ethiopia, it is common in the dry and moist Kolla agro-climatic zones of the Rift Valley in Gamo Gofa, and in Sidamo, Tigray, Welo, Shoa, Gojam, Ilubabor, Arsi, and upland Harerge regions. Its biophysical limits are: altitude 0–1800 m, mean annual temperature 20–30 °C, and mean annual rainfall 250–400 mm; the soils in its range tend to be deep sands, sandy clay loams, sandy loams, or clays. It has wide ecological distribution; however, it reaches its maximum development as an individual tree on low-lying alluvial sites with deep sandy loam and uninterrupted access to water, such as valley floors, riverbanks, or the foot of rocky slopes. It prefers open woodland or savannah for natural regeneration.

3.1.1.3 Uses

B. aegyptiaca is an important species for dry areas as it produces fruit even in very dry years. The wood is termite-resistant and potentially provides firewood, charcoal, timber (furniture), poles, utensils, tool handles, food (fruit), medicine (infusion from roots, emulsion from fruit, heated gum from the wood, fruits), fodder (leaves, young shoots, fruit), shade, mulch, windbreaks, gum, places for ceremonial meetings, fencing (cut branches), and oil (fruit); an emulsion of the fruit kills snails and fish (Azene 2007). The usually evergreen behavior potentially makes the tree an attractive element to introduce into shelterbelts; the tree is managed through agroforestry. It is planted along irrigation canals and is used to attract insects for trapping. The smaller trees and branches are used as living fences because they are resilient; the thorny cut branches are used to make livestock enclosures. The tree fixes nitrogen, the bark yields fibers, and the natural gums from the branches are used as glue.

3.1.1.4 Propagation Methods

Seedlings and direct sowing methods at site are mainly employed for *B. aegyptiaca* propagation. Seeds may be collected from fruit that is being processed for other purposes, from dung, and directly from the trees. The seeds are soaked in cold water for some hours and then the mixture is stirred vigorously. Seed germination can also be improved by immersing the seeds in boiling water for 7–10 min and then cooling the mixture slowly. Alternatively, seeds are collected from goats' droppings/secreta, which can easily be collected where this livestock is kept overnight. Seeds can germinate within 1–4 weeks (Azene 2007). The seed germination rate is 50–70%. Natural regeneration occurs primarily through seedlings. The fruit is in high demand, which gives it high economic value; therefore, little fruit and thus few seeds are left for natural regeneration of the species. The tree can also generate by coppice shoots and by its abundant root suckers.

3.1.1.5 Management

B. aegyptiaca is a relatively slow-growing tree; it produces root suckers if the roots are exposed. The tree coppices and pollards well and can regenerate after the occurrence of lopping and heavy grazing, but it is essential to protect young seedlings from grazing. Where fruit is the principal interest, pollarding and coppicing are seldom employed for obtaining fodder.

3.1.2 *Acacia tortilis* (Azene 2007)

3.1.2.1 Taxonomy and Description

Acacia tortilis belongs to the family Fabaceae. It has several vernacular names in different areas of Ethiopia, such as: in Afargna *behbey*; in Amharic *deweni grar*; in Oromigna *lotoba* and *tedecha;* in Sidamegna *abak*, *akab*, *kura*, *ora*, and *timad*; and in Tigrigna *akiba* and *aqba*; in English it is called umbrella thorn.

A characteristic tree of dry lands, *A. tortilis* grows to a height of 4–21 m, the crown is layered, flat, and spreading or rounded; sometimes the bark is gray or brown-black and fissured when mature (Fig. 19.2). Thorns are of two kinds, small

Fig. 19.2 *Acacia tortilis* trees (Azene 2007)

hooked and long, straight and white, sometimes occurring in mixed pairs all on one stem. The leaves are two to ten pairs of pinnae on a short stalk of only 2–4 cm. The flowers are fragrant, cream, and have round heads. The fruits, which are pale yellow-brown pods, each containing up to ten brown seeds, hang in dense bunches that are spirally twisted, sometimes in rings.

3.1.2.2 Ecology

Acacia tortilis is a common acacia in most of dry Africa from North and West Africa to South Africa. It is widespread in dry Bereha and dry and moist Kolla and in the Weyna Dega agroclimatic zones of the Afar plain, Bale, Arsi, Harerge, Shoa, western Welo, and western Tigray at 300–1900 m. It favors alkaline soils and can also grow in shallow soils. It produces enormous deep roots that penetrate a wide area to collect water.

3.1.2.3 Uses

Acacia tortilis is used for firewood, charcoal, timber, poles, posts, fodder (shoots, leaves, pods), bee forage, shade (livestock), nitrogen fixation, soil conservation, fiber (bark), fences (cut branches). The pods are an important source of fodder in the semi-desert areas of Africa.

3.1.2.4 Propagation

Acacia tortilis can be propagated by seedlings and wildlings, but the seeds have a low germination rate and the seed count is 12,000–31,000 per kg. Beetle infestation often lowers the germination rate. The seed is very hard. For germination, pour boiling water over the seed; allow to cool and soak for 24 h. The seeds can be stored for a very long period without losing viability if insect damage can be prevented.

3.1.2.5 Management

Acacia tortilis is slow growing, but if well managed, it grows relatively fast in dry sandy soils. Protect young plants from lopping by goats. Except in desert areas, the tree can be left to grow on pasture or crop land.

3.1.3 *Tamarindus indica* (Azene 2007)

3.1.3.1 Taxonomy and Description

Tamarindus indica belongs to the family Fabaceae. In Ethiopia it has different local names, such as *hamurto* (Afargna); *Humer* and *Roka* (Amharic); *roka* (Oromigna); and *humer* (Tigrigna); in English, it is called tamarind (Azene 2007). It is a large evergreen tree up to 30 m tall, the bole is usually 1–2 m diameter; the crown is dense, widely spreading, and rounded; the bark is rough, fissured, and grayish-brown (Fig. 19.3). The leaves are compound, on hairy stalks of up to 15 cm, with 10–18 pairs of leaflets, up to 3 cm, that are dull green and oblong, round at the tip and base, with veins raised. Small yellow flowers streaked with pink are contained in groups of 5–10 in drooping racemes 3–5 cm long; buds are red; the petals are golden with red veins. The fruits are pale brown, sausage-like hairy pods, which are typically leguminous in appearance, oblong, straight, or slightly curved, turning from green to dark brown as they ripen, cracking when mature to show a sticky brown pulp with around 110 dark brown angular seeds. The tree is slow growing but long lived. Individual trees commonly remain productive for 150 years or longer.

3.1.3.2 Ecology

Tamarindus indica is indigenous to tropical Africa; it is widely used in the Sahel and in India, Southeast Asia, the Caribbean, and Central America. A very adaptable species, it is drought hardy, preferring semi-arid areas and wooded grasslands,

Fig. 19.3 *Tamarindus indica* mature tree (Azene 2007)

tolerating salty, coastal winds, even monsoon climates; it grows in moist soils, but prefers well-drained deep alluvial soil, often riverine in very dry areas. In Ethiopia, it occurs in Bereha and in the dry and moist Kolla agroclimatic zones of most regions; its biophysical limits are: altitude 0–1500 m, mean annual temperature 47 °C, and mean annual rainfall of 350–1500 mm.

3.1.3.3 Uses

Potentially, *T. indica* is used for food (fruit and the fruit pulp for drinks; spice), mulch, nitrogen fixation, as a windbreak, and for fodder (leaves, fruit); the leaves have a high forage value, though rarely lopped for this purpose because lopping affects fruit yields. The flowers are reportedly a good source for honey production. The tree provides good firewood and charcoal. Its wood is very hard, durable, and strong and takes a fine polish. It is used for general carpentry, sugar mills, wheels, hubs, wooden utensils, agricultural tools, mortars, boat planks, toys, panels, and furniture. The bark tannins can be used in ink or for fixing dyes. The bark is astringent and tonic and its ash may be given internally as a digestive. Young leaves may be used in fomentations for rheumatism, applied to sores and wounds, or administered as a poultice for inflammation of joints to reduce swelling and relieve pain. The extended crown of the tamarind offers shade and is ornamental, so that it is used as a 'rest and consultation tree' in villages. The tree is commonly used for firebreaks, boundaries, and as a live fence. The evergreen habit and the beautiful flowers make it suitable for ornamental plantings in parks, and along roads and riverbanks.

3.1.3.4 Propagation

T. indica can be propagated by seedlings, wildlings, direct sowing at site, grafting, and budding stems, and air-layering for the best varieties. Treatment involves soaking the seeds in cold water for 12 h or nicking the seed. The fruit has 350–1400 seeds per kg and the germination rate is 90% within 40–50 days. Germination is best when seeds are covered with 1.5 cm loose, sandy loam or with a mixture of loam and sand. Seedlings should reach at least 80 cm before being transplanted to their final location at the beginning of the rainy season. Outstanding mother trees are propagated asexually.

3.1.3.5 Management

Growth of *T. indica* is generally slow, with seedling height increasing by about 60 cm annually. The trees require minimal care in pollarding and coppicing. When establishing a pure plantation, spacing should be at least 13 m × 13 m. The spacing distance can be reduced with vegetative propagated plants; smaller trees are easier to harvest. The tree may remain productive until it reaches old age, yielding up to 150 kg per tree or over 2 Mg ha^{-1} $year^{-1}$.

3.2 Effect of Salinity on Seed Germination

Seed germination is an important and vulnerable stage in the life cycle of terrestrial angiosperms and it determines seedling establishment and plant growth. Despite the importance of seed germination under salt-stress (Ungar 1995), the mechanism (s) of salt-tolerance in seeds is/are relatively poorly understood, especially when compared with the amount of information currently available about salt tolerance in plant physiology and biochemistry (Hester et al. 2001; Garthwaite et al. 2005; Kanai et al. 2007). Salinity impairs seed germination, reduces nodule formation, retards plant development, and reduces crop yield (Al-mutawa 2003; Debez et al. 2004). Germination and seedling parameters are the most viable criteria used for selecting salt tolerance in plants (Sosa et al. 2005; Jamil et al. 2006; Luna et al. 2008).

According to Kader and Jutzi (2004), in the presence of salinity, the rate and percentage of germination and the seed vigor index are related to the specific impact of ions and the reduction of environmental water potential. If salinity increases (reduction of environmental osmotic potential), the above seed parameters will be decreased. Increased salinity also reduces germination rates and seedling weight. Overall, salinity, through the enhancement of osmotic pressure, leads to a reduction of water absorbance; metabolical and physiological processes will be affected by this. Thus, salinity causes a delay in seed germination followed by an increase in the duration of germination (Kang and Saltveit 2002). Successful forest tree plantation in areas of increased salinity requires the recognition of salt-tolerant species, because tolerance to salinity during germination is critical for the establishment of plants growing in saline soil (Ramezani et al. 2010).

3.3 Effect of Salinity on Seedling Growth

Most landscape plants are sensitive to soil salinity. Tree seedlings and young transplants can be particularly sensitive to salt exposure. The severity of salt damage to plants depends upon the amount, duration of exposure, and the concentration of salt (Smith et al. 2009). An understanding of the responses of plants to salinity is of great practical significance. High concentrations of salts have detrimental effects on plant growth (Garg and Gupta 1997) and excessive concentrations kill growing plants (Donahue et al. 1983). Many investigators have reported retardation of the germination and growth of seedlings at high salinity (Bernstein 1962; Garg and Gupta 1997; Ramoliya et al. 2004). Increased salinity stress decreased almost all growth parameters (Razmjoo et al. 2008). Younis et al. (2008) reported that enhancing salinity treatments led to seedling growth reduction. However, plant species differ in their sensitivity or tolerance to salts (Brady and Weil 1996).

There are many different types of salts and an almost equally diverse set of mechanisms of avoidance or tolerance. In addition, organs, tissues, and cells at different developmental stages of plants exhibit varying degrees of tolerance to environmental conditions (Munns 1993). It is reported that soil salinity suppresses shoot growth more than root growth (Maas and Hoffman 1977; Ramoliya et al. 2004). Generally, in saline soil, salt-induced water deficit is one of the major constraints for seedling growth. The high salt content lowers the osmotic potential of soil water and, consequently, the availability of soil water to plants. In addition, salinity-stress affects nutrient uptake and transport, as well as the utilization of different nutrients (Grattan and Grieve 1999).

3.4 Effect of Multi-purpose Trees on Soil Fertility Management

The potential of trees for the reclamation of salt-affected areas has been increasingly recognized in the past few decades (Allen et al. 1994). There has been a major emphasis on growing trees in saline lands to prevent desertification. Increased forestation can improve soil health in many ways, such as by the impact it has on soil organic matter (including the decomposition of roots) and the microclimate; reducing evaporation; releasing protons and organic acids in the rhizosphere; changing water infiltration; and improving soil aeration and porosity. Hence, the plantation of trees with different salinity-tolerant properties in highly saline soils can better sustain soil health and economic growth than can agronomic crops (Qureshi et al. 1993). However, studies have shown considerable variation among tree species in their abilities to tolerate salt and there is ample chance for the identification of salt-tolerant species according to the habitat conditions (Wood and Awang 1998).

Research results for different trees, such as *A. tortilis* (in the Rift Valley) and *A. nilotica* (in the Middle Awash) have shown that scattered agroforestry trees play an important role in soil fertility enrichment. These trees significantly improved the soil properties of different soil types under their canopies as compared with the soil properties of the adjacent open land. The soil patches found under tree canopies are important local nutrient reserves that influence the rural landscape. These trees have the potential to provide nutrients to support crop and livestock production for smallholder farmers (Abebe et al. 2006).

Smallholder farmers have recently started to use short-term planted fallows with leguminous trees to regenerate the fertility of their soils more rapidly than with natural fallows; these trees also act as a substitute for mineral nitrogen fertilizer, which is often too expensive for the farmers to purchase (Kwesiga et al. 1999). Less visibly, but no less importantly, trees play a crucial role in maintaining and regenerating soil fertility through the action of their roots and litter. Therefore, tree planting

Table 19.1 Effects of multipurpose trees on soil properties

	AWC m^3 m^{-3}	pH	EC$_e$ (dS m^{-1})	Bulk density (g cm^3)	Porosity (%)	PI
Species	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Species						
Balanites aegyptiaca	0.10 ± 0.01c	8.14 ± 0..08c	1.71 ± 1.1a	1.47 ± 0.1a	46 ± 4b	0.100 ± 0.1a
Acacia tortilis	0.14 ± 0.01a	8.30 ± 0.08a	2.48 ± 1.1b	1.09 ± 0.1c	59 ± 3a	0.098 ± 0.1a
Tamarindus indica	0.13 ± 0.01b	8.23 ± 0.08b	2.91 ± 1.1c	1.41 ± 0.1b	48 ± 5b	0.053 ± 0.1b
Pr > F	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
Radii						
Base	0.13 ± 0.01a	8.0.27 ± 0.1a	1.83 ± 0.9c	1.27 ± 0.2c	52 ± 7a	0.111 ± 0.1a
Crown	0.12 ± 0.01a	8.23 ± 0.1b	2.31 ± 1.1b	1.32 ± 0.2b	51 ± 6a	0.071 ± 0.1b
Outside	0.12 ± 0.02a	8.17 ± 0.1c	2.96 ± 1.5a	1.37 ± 0.2a	50 ± 6a	0.070 ± 0.1b
Pr > F	0.4879	<0.0001*	<0.0001*	<0.0001*	0.3321	<0.0001*
Depth (cm)						
0–25	0.13 ± 0.01a	8.24 ± 0.1a	1.91 ± 1.2b	1.3 ± 0.2b	52 ± 6a	0.125 ± 0.1a
25–50	0.12 ± 0.01a	8.20 ± 0.1b	2.82 ± 1.2a	1.34 ± 2a	50 ± 7a	0.042 ± 0.1b
Pr > F	0.2063	<0.0001*	<0.0001*	0.0006*	0.1406	<0.0001*

Mean values are shown for pH, electrical conductivity (EC$_e$), available water capacity (AWC), bulk density (BD), total porosity (P), probability value (Pr), F test statistic (F), and the productivity index (PI). Mean values with the same letter within the same column are not significantly different at ($p < 0.05$) according to the least squares mean difference (LSD) method

*Significant at $p < 0.05$

remains the most suitable option for soil stabilization, improvement of productivity, and enhancement of biodiversity in salt-affected areas, as woody plants are more tolerant to salinity than agricultural crops (Kozlowski 1997).

In our study, available water capacity at the base (0–25 cm) soil depth was generally higher in *A. tortilis* than in *T. indica* and *B. aegyptiaca*. However, the available water capacity of the three study tree species consistently remained the same with increasing depth and radii (Table 19.1). Higher porosity (59%) was found in *A. tortilis* at the tree base (0–25 cm) (Table 19.1). The net result of this finding is that the voids between the soil aggregates will be relatively larger, the soil will remain permeable, and this enhanced aggregation will be beneficial in terms of soil aeration, root penetration, and root growth (Buckman and Brady 1967). However, *B. aegyptiaca* and *T. indica* had higher bulk density (BD) than *A. tortilis,* and this higher density changes the soil's porosity and its ability to hold water, leading to reduced opportunity for root growth and soil productivity.

We found that electrical conductivity (EC$_e$) values at the bases of the study tree species were lower than 2 dS m^{-1} and increased down to a soil depth of 25–50 cm and from the base to outside the tree crown (Table 19.1). Similar results were obtained by Rodrigue and Burger (2004), in that all textured soils and usually sandy loam and loam textures had low EC_e values, and finer textures were more commonly associated with higher EC_e levels. The elevated salt concentration down in the subsoil had a positive effect on enhancing or stabilizing soil aggregation and increasing the infiltration rate, but had a negative and potentially lethal effect on plants (Western Fertilizer Handbook 1995; Barbour et al. 1998; Miller and Donahue 1995; USDA Natural Resources Conservation Service 2002). The results of our study indicated that EC_e and BD increased with increasing soil depth and radii, while pH and porosity decreased with increasing soil depth and radii (Table 19.1).

Species, radii, depth, and their interaction had a significant difference with respect to pH, EC_e, BD, and PI ($p < 0.05$). In the study species, *A. tortilis* had high measured soil parameter values, particularly at the base of the tree, followed by *B. aegyptiaca*. Pierce et al. (1983) confirmed that BD, soil pH, available water capacity, and soil depth values were high in the topsoil and did not limit soil productivity. This result is in agreement with Anikwe (2000), who reported that deep soils without limitations promoted root proliferation. This would enable plant roots to explore more areas for nutrients and water. However, for all three tree species we studied, the mean values of these soil parameters decreased down the profiles (Table 19.1). These findings implied that the assessed productivity indicators could limit crop production in the subsoil.

3.5 Effect of Salinity on Soil Chemical Properties

Different salinity levels had a significant effect on pH, EC_e, OC, and CEC (cation exchange capacity) ($p < 0.05$). The interaction between salinity level and species exhibited a significant effect in most of the post soil chemical analysis ($p < 0.05$). Maximum and minimum soil pH values of 8.4 and 8.1 were recorded in *B. aegyptiacaand A. tortilis*, at 10 dS $m^{-1}$and 4 dS m^{-1}, respectively. There was a 20–40% increment in the soil pH from 4 to10 dS m^{-1}. *B. aegyptiaca* and *T. indica* increased the soil pH more significantly than *A. tortilis* (Table 19.2). The highest and lowest EC_e values, of 5.2 and 2.2 dS m^{-1}, were recorded in *T. indica* and *B. aegyptiaca*, at 12 and 4 dS m^{-1}, respectively. There were 40–50% decrements from the initial EC_e value at each salinity level of the soil. Of the three study species, *B. aegyptiaca* significantly cleared the effect of salinity, from 4 to 10 dS m^{-1} (Table 19.2).

Moreover, as the salinity level increased the soil OC decreased. There was a 20–30% decrement in OC from the initial level, at 4–12 dS m^{-1}. Of the study species, *A. tortilis* appeared to be the most efficient remover of OC compared with the other tree species. In all three tree species, the CEC values in salinized soil were significantly lower than that in the control soil. There was a 20% decrement in CEC compared with that in the initial soil. CEC was more highly reduced in *A. tortilis*, at 12 dS m^{-1}, than in the other species. This could have been due to some amount of Ca^{+2} and Mg^{+2} being taken up by the plant (Table 19.2). There was a 14,6 to 30.3% reduction from the initial 6.36 SAR value in different species at salinity 12 dS m^{-1}. Except at 12 dS m^{-1}, statistically the SAR values between treatments tended to remain similar. *T. indica* had a more highly reduced SAR value than the other study

Table 19.2 Effect of salinity on soil properties

	pH	EC_e (dS m^{-1})	OC (%)	CEC (cmol $^{(+)}$ g^{-1})	SAR
EC_e level dSm^{-1}	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Balanites aegyptiaca					
Before experiment	8.05	4.06	1.02	43	6.36
4	8.25 ± 0.1b	2.2 ± 0.1d	0.82 ± 0.01a	40 ± 0.5a	5.86 ± 0.2a
6	8.32 ± 0.1ab	3.2 ± 0.3c	0.70 ± 0.01b	38 ± 0b	5.56 ± 0.1a
8	8.44 ± 0.1a	3.6 ± 0.1b	0.80 ± 0.01a	37 ± 1b	5.53 ± 0.08a
10	8.41 ± 0.1a	3.7 ± 0.01b	0.71 ± 0.02b	37 ± 0.5b	5.46 ± 0.4a
12	8.39 ± 0.1a	4.4 ± 0.6a	0.57 ± 0.03c	37 ± 1b	5.43 ± 0.57a
Pr > F	0.0413*	0.0001*	< 0.0001*	0.0011*	0.5383
Acacia tortilis					
4	8.18 ± 0.1b	2.3 ± 0.15b	0.62 ± 0.02b	38 ± 1.2ab	5.50 ± 0.06a
6	8.28 ± 0.04a	3.6 ± 0.09a	0.76 ± 0.04a	38 ± 2.6a	5.12 ± 0.3a
8	8.29 ± 0.01a	3.7 ± 0.01a	0.68 ± 0.01ab	38 ± 3ab	5.03 ± 0.6a
10	8.34 ± 0.01a	3.7 ± 0.13a	0.75 ± 0.03a	37 ± 2ab	5.01 ± 0.02a
12	8.36 ± 0.01a	3.8 ± 0.12a	0.60 ± 0.04ab	34 ± 0.5b	4.97 ± 0.2a
Pr > F	0.0310*	0.0035*	0.0040*	0.0240*	0.2252
Tamarindus indica					
4	8.23 ± 0.02c	3.4 ± 0.46d	0.79 ± 0.04a	36 ± 2.5a	5.31 ± 0.2a
6	8.37 ± 0.01a	3.8 ± 0.7 cd	0.83 ± 0.05a	37 ± 2.1a	4.95 ± 0.3ab
8	8.38 ± 0.03a	4.2 ± 0.04bc	0.77 ± 0.04a	38 ± 2.1a	4.89 ± 0.4ab
10	8.42 ± 0.04a	4.6 ± 0.09ab	0.77 ± 0.03ab	37 ± 1.3a	4.90 ± 0.2ab
12	8.31 ± 0.02b	5.2 ± 0.18a	0.70 ± 0.02b	32 ± 1.0b	4.43 ± 0.3b
Pr > F	<0.0001*	0.0136*	0.0332*	0.0135*	0.0900

SAR Sodium absorption ratio

*Significant at $p < 0.05$. Mean values with the same letter within the same column are not significantly different at ($p < 0.05$)

species (Table 19.2). The soil was rich in exchangeable Ca^{+2}, Mg^{+2}, and Na^{+}; the high temperature of the area and the greater clay content in the control soil could explain why the SAR values were similar at all salinity levels.

3.6 Effect of Multipurpose Tree Species on Soil Productivity Index

The productivity index of the soil samples differed among the soil series and the tree species. There were significant differences in soil productivity potential among the tree species studied ($p < 0.05$). The productivity indices at the base and at the crown of the tree were significantly higher than the values outside the tree crown for all three studied tree species. The maximum and minimum productivity index values; namely, 0.325 and 0.040, were recorded in *A. tortilis* and *T. indica*, respectively (Table 19.3). The soil productivity index of the tree species decreased with soil depth and from the base of the tree to outside the crown. *A. tortilis* had a higher

Table 19.3 Effect of multipurpose tree species on soil productivity index

Species type			
	B. aegyptiaca	*A. tortilis*	*T. indica*
Soil depth and radii	Mean ± SD	Mean ± SD	Mean ± SD
Base (0–50 cm)	0.253 ± 0.058a	0.325 ± 0.108a	0.222 ± 0.044a
Crown (0–50 cm)	0.191 ± 0.018b	0.201 ± 0.020b	0.055 ± 0.016b
Outside (0–50 cm)	0.133 ± 0.038c	0.064 ± 0.016c	0.040 ± 0.002b
Pr > F	<0.0001*	<0.0001*	<0.0001*

*Significant at $p < 0.05$. Mean values are shown for the productivity index (PI) of four replicated soil samples for each tree species. Mean values with the same letter within the same column are not significantly different at ($p < 0.05$) according to the least squares difference (LSD) method

Table 19.4 Soil productivity index (PI) ratings of multipurpose tree species

Species type			
	B. aegyptiaca	*A. tortilis*	*T. indica*
Soil depth and radii	PI rating	PI rating	PI rating
Base (0–50 cm)	Moderate	High	Moderate
Crown (0–50 cm)	Moderate	Moderate	Low
Outside (0–50 cm)	Moderate	Low	Low

productivity index value than *B. aegyptiaca* and *T. indica* (Table 19.4). This higher value could be attributed to the tree species' potential for the addition of organic matter and its dense rooting depth. The results revealed that trees with the highest productivity index rating are more suitable for? and can sustain crop production for a longer period than trees with a lower productivity index rating under similar management practices.

4 Conclusions

Salinity had a significant effect on seedling performance in all three of our study species. Increasing the salt levels caused a significant reduction in height and in stem and root dry weights for the three species. Based on seedling growth parameters, *B. aegyptiaca* appeared to be salt-tolerant even at a high level of salinity (12 dS m^{-1}), while *T. indica* was moderately tolerant. At the seedling stage, *B. aegyptiaca* and *T. indica* were found to be more efficient salt cleansers than *A. tortilis* in their response to post chemical soil property. Salinity and the interaction of species and salinity level had significant effects on all seedling growth parameters and soil chemical properties, which indicated salinity as a limiting factor for plant growth. Salinity had a significant effect on the productivity index, with *A. tortilis* and *B. aegyptiaca* contributing more to soil productivity improvement than *T. indica*. Further, the top (0–50 cm) soil depth at the base of a tree had a higher soil productivity index than other soil radii. In conclusion, A. *tortilis* was found to be salt-tolerant, and this tree species showed the most potential for soil productivity improvement, followed in this parameter by *B. aegyptiaca* and *T. indica.* Therefore, we suggest that *A. tortilis* and *B. aegyptiaca* could be suitable for reclamation in arid and semi-arid areas where salinity affects crop development, either in an agroforestry system or in strip tree planting practices.

5 Recommendations

- To derive an optimum tree and under-canopy crop yield, the use of *A. tortilis* and *B. aegyptiaca* as agroforestry trees in a saline environment should be emphasized.
- Restoration and afforestation with these species can halt further expansion of salinization and change the microclimate of the area in which they are planted.
- Appropriate environmental plans should be prepared before irrigation development is implemented.
- Government policy should focus on the protection, management, and proper utilization of indigenous tree species in arid and semi-arid areas.

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Chapter 20
Homegardens: Drops to Sustainability

S. Chakravarty, A. Puri, Mohit Subba, N. A. Pala, and G. Shukla

Abstract Homegardening is an ancient and widespread practice of deliberate mixing of field crops, herbs and shrubs with trees and livestock within the compound of a house, popular in regions with either high or low human population densities in developing and developed countries. They reflect the wisdom of traditional culture and ecological knowledge that have evolved over the years. The gardens resemble the structure of natural ecosystems, i.e. they create a forest-like multi-storey canopy structure on a land marginal to field production and labour marginal to major household economic activities. Multiple environmental and ecological benefits are realized from homegardens in terms of ecologically friendly approaches for food production improving food security and enhancing economic growth along with biodiversity and natural resources conservation. As homegardens are time-tested local strategies that are widely adopted and practiced in various circumstances by local communities with limited resources and institutional support, they can be a part of agriculture and food production systems in many developing countries and are widely used as a remedy to alleviate hunger and malnutrition in the face of a food crisis particularly in a climate change world.

Keywords Family farming · Homegarden · Homestead · House owner · Resource starved · Small land owner · Biodiversity conservation · Ecological benefits

1 Introduction

The theme for United Nations' World Food Day on 16 October 2014 was 'Family Farming' in homegardens. Homegarden or mixed, kitchen, backyard, farmyard, compound or homestead garden (Terra 1958; Ruthenberg 1980; Puri and Nair 2004; Rowe 2009) is an agroforestry practice known to be the oldest (next only to shifting

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cultivation) and ecologically sustainable land use activity developed by numerous human cultures worldwide (Sommers 1982; Christanty 1990; Kumar and Nair 2004; Mekonnen et al. 2014). Homegarden agroforestry is a deliberate land use management of multipurpose trees and shrubs in intimate association with agricultural crops and livestock within the compounds of individual houses and being intensively managed by family labour (Nair 1989, 1993, 2008; Fernandes and Nair 1986; Nair and Sreedharan 1986; Kumar 1994, 1999a, b, 2003; Kumar et al. 1994; Kumar and Nair 2004, 2006). Globally, homegardens have been documented as an important supplemental source contributing to food and nutritional security and livelihoods (Galhena et al. 2013).

2 Distribution

Homegardens are ecologically divided into tropical and temperate (Ninez 1984), found in both rural and urban areas in predominantly small-scale subsistence agricultural systems (Nair 1993). The gardens are popular in regions with either high or low human population densities in developing and developed countries of five continents (Ninez 1984). In India these gardens are generally found in high rainfall areas at Andaman Islands, Kerala, northeast and central India, parts of Karnataka and West Bengal (Jose and Shanmugaratnam 1993; Kumar et al. 1994; Dagar 1995; Ramakrishnan et al. 1996; Santhakumar 1996; Kumar 1997, 1999a, b, 2000, 2003, 2005, 2006a, b, c, 2007, 2008a, b, c, d, 2011; Godbole 1998; Sinha and Das 2000; Ramakrishnan 2001; Kumar and Kumar 2002; Kumar and Peter 2002; Shastri et al. 2002; Deppommier 2003; Samati 2004; Das and Das 2005; Krishnankutty 2005; Shrivastava and Heinen 2005; Mohan et al. 2006, 2007; Peyre et al. 2006; Kumar and Takeuchi 2009; Tangjang and Arunachalam 2009; Devi and Das 2010; Panwar and Chakravarty 2010; Sahoo et al. 2010; Tynsong and Tiwari 2010; Saikia and Khan 2011; Saikia et al. 2012; Zimik et al. 2012; Dagar et al. 2014).

3 Characteristics

The general tendencies of homegarden food production system based on 15 type-specific characteristics that present an ethnographical synthesis of homegardens across the globe are given in Table 20.1 (Ruthenberg 1980; Ninez 1987).

4 Structure of Homegardens

The environmental factors where the homegarden is located and available family resources like labour, skills, preferences and enthusiasm of family members (Christanty et al. 1986; Asfaw 2002; Galhena et al. 2012) along with owner's

Table 20.1 The key characteristics of a typical homegarden

Characteristic	General practice
Species density	High
Species type	Staples, vegetables, fruits, medicinal plants
Production objective	Home consumption
Labour source	Family (women, elderly, children)
Labour requirements	Part-time
Harvest frequency	Daily, seasonal
Space utilization	Horizontal and vertical
Location	Near dwelling
Cropping pattern	Irregular and row
Technology	Simple hand tools
Input cost	Low
Distribution	Rural and urban areas
Skills	Gardening and horticultural skills
Assistance	None or minor

Source: Niñez (1987)

decisions related to the selection of crops, procuring inputs, harvesting, management, household consumption and income generation needs (Ali 2005; Galhena et al. 2012) make the structure, function, composition and appearance of every homegarden unique (Ninez 1984; Fernandes and Nair 1986; Nair 1989; Torquebiau 1992), and thus their cultivation tends to be quite dynamic (Sthapit et al. 2004; Eyzaguirre and Linares 2010). Structure, composition, intensity of cultivation and diversity of homegardens are also subjected to the socioeconomic status of the household (Wiersum 2006). Overall the planting/growing of food and non-food crops and animals in the garden is influenced by ecological potential, economic status and social elements (Abdoellah et al. 2006; Peyre et al. 2006).

Homegardens exhibit complex arrangement of plants both vertically and horizontally (Panwar and Chakravarty 2010). Vertical arrangement is a result of variation in total height of the plants at their maturity, while horizontal arrangement is due to intermixing of the species and individuals. The choice of plant species and their arrangement and management vary between and within tropical homegardens in the same community (Mendez et al. 2001). Different agroecological and socioeconomic conditions determine significant variations across agroecosystems in terms of its size (Galluzzi et al. 2010). Generally, in homegardens representing a niche within larger farming systems, their size is to some degree proportional to the size of the overall farm (Guarino and Hoogendijk 2004). The homegarden size varies from household to household, and normally their average size is less than that of the arable land owned by the household. Homegardens may be small (less than 1000 m^2), intermediate (1000–2000 m^2) and large, i.e. more than 2000 m^2 in Mexico (Van der Wal and Bongers 2013) or 0.21, 0.73 and 1.5 ha, respectively, in *Terai* region of West Bengal, India (Subba 2014).

5 Function and Use of Homegardens

The high diversity of species in homegarden have wide socioeconomic and agroecological roles including production of food and a wide range of other products such as firewood, fodders, spices, medicinal plants and ornamentals (Udofia et al. 2012) and avoidance of environmental deterioration of climate-related hazards commonly associated with monoculture production systems (Fernandes and Nair 1990; Albrecht and Kandji 2003) and income-generating sites (Shoo 2009). The diversity of plants in the homegarden associated with other organisms contribute to the formation and maintenance of soil structure and retention of moisture and nutrient levels and promote the recycling of nutrients, which reduces ecosystem vulnerability to climate change (Verchot et al. 2007). Further, they represent an operational farm unit which integrates trees with field crops, poultry and/or fish (Rico-Gray et al. 1991; Singh 1987), having the basic objective of ensuring sustained availability of multiple products such as food, vegetables, fruits, fodder, fuel, timber, medicines and/or ornamentals (Michon et al. 1983; Dagar 1995; Polegri and Negri 2010) besides generating employment and cash income (Padoch and de Jong 1991; Soemarwoto and Conway 1991). Urban and suburban homegardens are ensuring the food, breeding sites and shelter for animal and plants as well as modifying microclimate (Smith et al. 2006).

Homegardens are often utilized as testing plots for new crops, as nurseries for plantlets later destined for planting in open fields and as sites for domestication of weedy forms which may also be used directly within the household (Blancas et al. 2010, 2013; Parra et al. 2010). As homegarden is adopted predominantly for subsistence needs with flexibility in farming practices, introduction and maintenance of wild species (Guijt et al. 1995), indigenous crops (Juma 1989) and traditional varieties (Negri 2003; Negri and Polegri 2009) lead to significant intraspecific diversity (Eyzaguirre and Linares 2004) that not only increases a species' chance for adaptation and survival over time (Soule 1987; Nunney and Campbell 1993) but also provides crucial material for breeding (Tanksley and McCouch 1997; Feuillet et al. 2008) and for establishing complementing or restoring germplasm collections (Castineiras et al. 2007).

The increasingly important urban gardens which are no longer connected to larger agroecosystems contribute to improving air quality, reducing CO_2 emissions and temperatures and providing citizens with livelihood opportunities as well as social and recreational activities (Van Veenhuizen 2006; Viljoen et al. 2009). Home gardens help ensure food security for rural people, in particular for poor farmers. They can be a buffer maintaining the sustainability of rural livelihoods (Aumeerudy and Sansonnens 1994; Eyzaguirre and Watson 2001; Alfred 2009). Home gardens assist in protecting the environment (Alavalapati et al. 2004).

6 Cultural Association

Home gardens are essentially man-made and reflect the wisdom of traditional culture and ecological knowledge that have evolved over the years. Such valuable traditional ecological knowledge systems are based on strong sociocultural and traditional beliefs confounded by the economic status of the people (Okigbo 1990). The gardens are designed and managed appropriately based on indigenous knowledge. They harbour a wide diversity of local crops suited to social and traditional significance and are the most promising and ecologically feasible option for the community. The indigenous knowledge used by the communities after repeated trial and error is now being regarded as an invaluable resource of agri-diversity (Collins and Qualset 1998). It is believed that traditional homegarden practices depend on the type of human community, tradition, needs and beliefs (Tangjang and Arunachalam 2009). Homegardens are the sites that have long been considered as signs of prestige and pride (Zemede and Ayele 1995; Zemede 1997) by the community on top of their key economic roles.

7 Benefits of Homegardens

Homegardens are a ‘place for innovation’ with the potential to improve the livelihood of peri-urban and rural communities (Landon-Lane 2011). The key benefits of homegardens described by Landon-Lane (2011) are given in Table 20.2. However, benefits of homegardening were broadly categorized into social, economic and environmental (Galhena et al. 2013).

8 Conclusions

The future of traditional homegardens and the genetic reservoir they contain is threatened now (Galluzzi et al. 2010). Modern and high-yielding varieties had replaced local landraces, but without optimum inputs and proper geographical or

Table 20.2 The key benefits of homegardening

Improved food security
Increased availability of food and better nutrition through food diversity
Income and enhanced rural employment through additional or off-season production
Decreased risk through diversification
Environmental benefits from recycling water and waste nutrients; controlling shade, dust and erosion; and maintaining or increasing local biodiversity

technical reasons, they still perform poorly compared to adapted landraces (Ceccarelli 1996). The latter, if they are retained at all, survive in low numbers in family farms and homegardens, and there is concern that their potential is not fully realized (Newton et al. 2010). Studies of traditional agricultural systems in tropical regions of the world can provide important information for understanding ecological processes associated to sustainable management of natural resources (Gliessman 2002). Homegardens present an excellent opportunity to use and experiment with both informal and formal techniques to collect qualitative as well as quantitative data (Vogl et al. 2004).

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Chapter 21

Installation of Silvopastoral Systems with Poplar in the Delta of the Paraná River, Argentina

Edgardo A. Casaubon, P. S. Cornaglia, and P. L. Peri

Abstract The establishment of silvopastoral systems (SSP) in poplar (*Populus deltoides* 'Australiano 106/60') plantations requires specific management strategies. In this context, the combination of the type of tree multiplication material and its palatability may determine the success of SSP establishment. We proposed to create a new technology for the establishment of a SSP with poplar for cattle and multiple uses such as wood production. The first objective was to assess changes in size and morphological characteristics for poplar pole cuttings grown at different densities in a nursery to test suitable multiplication materials for SSP establishment. The second objective was to determine the effect of pole cutting size (or age) on tree growth and sensitivity to damage caused by cattle browsing. In nursery, results showed that the production of multiplication material from larger spacing resulted in better 1-, 2- and 3-year-old pole cuttings, with higher diameter at breast height (DBH), total height, aerial biomass, straightness, conicity and shaft stability. In the poplar SSP, it was determined that the use of pole cuttings with a DBH equal or greater than 6 cm allowed the entry of cattle after the first years of plantation. Poplar leaves and tender branches obtained after spring pruning provided a good supplement to animal diet due to its higher values of crude protein, P and K content and digestibility. It was concluded that the use of poplar pole cuttings as multiplication material promotes the growth of natural pastures and early beef production in poplar SSP on the Lower Delta of the Paraná River.

Keywords *Populus deltoides* · Silvopasture · Aerial biomass · Animal behaviour · Delta of the Paraná River

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1 Overview

As an agroforestry practice, silvopasture is specifically designed and managed to produce trees, forage and livestock (Nair 1989). The trees are managed to obtain high-quality wood and to provide shade and shelter for the livestock (Klopfenstein et al. 1997; Gakis et al. 2004). This combination provides beneficial interactions that produce a practical and economical system for farmers (Clason 1998). Silvopastoral systems (SPSs) with poplars of high-quality wood production are a suitable option for use in different countries (Sanhueza 1998b; Sing et al. 1993; Addlestone et al. 1999; Sibbald et al. 2001; Burguess et al. 2004; FAO 2004; Thevasthasan and Gordon 2004; Sotomayor et al. 2004; Suárez 2004; Shuren and Stanton 2005; Clavijo et al. 2005; Daversa 2005; Shengzuo et al. 2005; Douglas et al. 2006; Yang et al. 2006; FAO 2008; Peri 2012; Peri et al. 2016). In fact, 65% of the area cultivated with poplars (*Populus* spp.) is used in agroforestry (Ball et al. 2005). In Argentina, the area cultivated with poplars that are part of agroforestry systems spans 20,500 ha, 50% being owned by private companies and the remaining 50% being owned by small-scale producers (FAO 2012). The area cultivated with Salicaceae in the Lower Delta of the Paraná River is estimated in 80,000 ha (75% of these under management), 14,000 ha of which is planted with poplars, with average yields of 20–25 m^3/ha/year, and the remaining hectares being planted with willows (MAGyP 2011). In the Lower Delta, also known as the Low Delta (Bonfils 1962), the core forest area (covering around 60,000 ha) has an endyked surface suitable for the implementation of SPSs with poplars spanning (Casaubon et al. 2016) an estimated 48,000 ha (Gaute et al. 2007).

SPSs with Salicaceae have distinctive features that must be taken into consideration to ensure the successful installation of the system. The poplar species is highly appetising to livestock (Lefroy et al. 1992; Taranaki Regional Council 2001). In addition, the potential damage by livestock to the planted trees in the SPS is inversely related to the availability and quality of understorey forage (Simón et al. 1998). This chapter evaluates the planting of large individuals (pole cuttings of different ages) to bring earlier the entry of cattle to the system. There are records of the introduction of livestock in the third year with the use of 1- and 2-year-old rooted pole cuttings (Suárez and Borodowski 1999) or 2-year-old unrooted pole cuttings (Ulloa and Villacura 2005). The diameters of older *P. deltoides* pole cuttings with good root biomass allow the introduction of cattle to SPSs without the need to protect each tree individually (Casaubón 2003). This minimises the costs of implementing the system. In this sense, knowledge on the establishment of SPSs is limited (Peri 2006).

Creating new technology for the installation of SPS designed to produce quality poplar wood is another challenge. The silviculture in Argentina to produce poplar wood for veneer and sawing in SPSs has not been sufficiently investigated. Nurseries are designed to produce linear metres of poles, which will later provide cuttings, and not volume of individual poles as proposed in this manuscript. Consequently, a high percentage of the pole cuttings that are currently used as planting material has a low and heterogeneous volumetric development and forms defects and health problems, which affect the quality and yield of the plantations intended for veneer and sawing. Salicaceae used in forestry are light-demanding heliophilous species that carry out intensive photosynthesis (FAO 1980). There is a linear relationship between dry matter production in poplars and the amount of light intercepted by the leaves. Therefore, any factor that affects the leaf area, or the efficiency of the conversion of intercepted light to biomass, produces a critical imbalance (Hinckley et al. 1992). According to Ericsson et al. (1992), there is a direct relationship between the amount of light received at a given site and the productivity of the poplar. Meanwhile, phototropism causes stems to curve towards the light (FAO 1980), leading to undesirable deformations in the stem (Sanhueza 1998a). Despite the potential benefits of SPSs, very little research had been done into the early establishment of deciduous species with the aim of producing high-quality wood. For this, the following objectives were:

To characterise the effect of light intensity on the size and quality of *P. deltoides* 'Australiano 106/60' pole cuttings potentially suitable for installing an SPS.

To determine the effect of the size and/or age of the *P. deltoides* 'Australiano 106/60' pole cuttings on their relative growth rate and susceptibility to damage due to cattle grazing in an SPS.

1.1 *Effect of Light Availability in the Nursery on the Size and Quality of* **P. deltoides** *'Australiano 106/60' Pole Cuttings for Use in Silvopastoral Systems*

The most commonly used way of establishing commercial poplar plantations in Argentina and in many countries around the world is to use 0.70-metre-long cuttings as propagation material. However, these cuttings regularly present growth problems because of topophysis (Alonzo and Sancho 1964; Bunse and Cerrillo 1988), cyclophysis (Martínez Pastur et al. 1994) and/or rooting (Martínez Pastur et al. 1994; Carmona et al. 1985), as well as cultural practices that influence the success of rooting (Frison 1972; Edwards and Kissock 1975), competition with weeds (FAO 1980), losses due to late frost and attack by leafcutter ants (Casaubón et al. 2011). This can lead to loss of plantation volume and very heterogeneous growth in the stands.

Commonly, when a SPS is established using pole cuttings, the introduction of animals is delayed for 4 or 5 years. Furthermore, if the propagation material does not have a good diameter and height, significant plant losses can occur due to rooting difficulties (Corcuera et al. 2005). Poplar tree leaf palatability and forage value for different types of livestock is also very well-known (Carou et al. 2010; Thomas 2011). This makes losses due to herbivory and/or mechanical damage frequent in SPSs. Therefore, the challenge is to produce propagation materials of suitable size to allow the entry of cattle into the SPS earlier, minimising plant loss due to knockdown, breakage and/or bark stripping. An alternative used in other countries is to use larger, older, rootless pole cuttings as planting material (FAO 1957; May 1959; Prevosto 1971; Vidali 1973; Mantovani 1993; Sanhueza 1998a). Such pole cuttings exhibit good rooting percentage, surpassing cuttings in numerous *P. deltoides* commercial clones (Casaubón et al. 2001). We aimed to evaluate the effect of nursery planting spacing on the size and morphological characteristics of *P. deltoides* 'Australiano 106/60' pole cuttings, propagation materials potentially suitable for installing an SPS. We tried to answer the following questions:

- How are the canopy structure and the light microenvironment related? This was done by using parameters estimated with the use of hemispheric photography and the diameter at breast height (DBH) and total height (Ht) variables for each density.
- How is the aerial and underground biomass of the poplar pole cuttings accumulated and partitioned at different spacings?
- At what age and planting spacing are the pole cuttings that are the straightest and most resistant to mechanical damage in an SPS produced?
- What relationship is there between leaf area, specific leaf area and the accumulation of biomass at different planting spacings?

The following hypotheses were established: (1) In an SPS of *Populus deltoides* 'Australiano 106/60', the greater availability of light in the nursery has a direct effect on the size of the pole cuttings produced. (2) The accumulation of biomass, the size of the pole cuttings, their straightness and height-to-diameter ratio, the leaf area and the specific leaf area in the nursery are directly related to spacing.

Sixteen plots with a surface area of 36 m^2 were installed in a randomised complete block experimental design (RCBD) with four replications set up. The treatments were four planting densities: 0.6 m × 0.6 m, 0.8 m × 0.8 m, 1 m × 1 m and 1.2 m × 1.2 m. The experiment was carried out using 0.70-metre-long cuttings as propagation material. Diameter at breast height (DBH) and total height (Ht) of the nine pole cuttings in the centre of each plot were measured. A calliper was used to measure the DBH and a fibreglass telescoping measuring rod was used to measure Ht (Fig. 21.1).

Significant interaction ($p \leq 0.0001$) was found between density and the year of planting for both DBH and Ht (Fig. 21.2). Three years after the installation of the nursery, the cuttings with the widest spacings had increased by 74% DBH and 50% Ht ($p \leq 0.05$).

In the nursery, older pole cuttings and wider spacing produced pole cuttings that are more uniform in size than in narrower spacing. According to Cannell (1999), the variability in productivity can be explained by the differences in the amount of radiation absorbed by the crown, by the efficiency with which the absorbed energy becomes biomass or by both factors. Meanwhile, all conditions favouring photosynthesis, and consequently the production of carbohydrates, increase the rooting capacity of propagation materials (Molnar and Culmming 1968). All of these characteristics have a positive impact on the homogeneity of the resulting stands.

Fig. 21.1 Trial of different plant spacings (0.6 m × 0.6 m, 0.8 m × 0.8 m, 1 m × 1 m and 1.2 m × 1.2 m) to produce *Populus deltoides* ‘Australiano 106/60’ pole cuttings, at 1 year of age

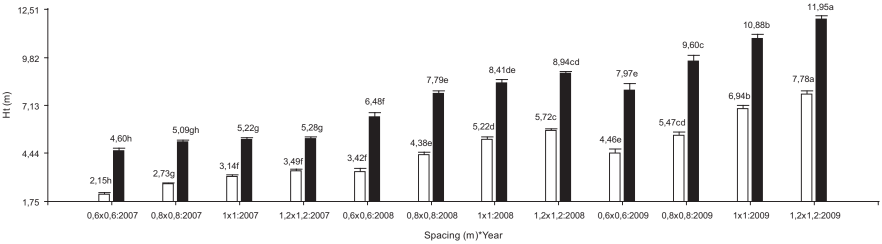

Fig. 21.2 Average diameter at breast height (DBH) and total height (Ht) of *Populus deltoides* ‘Australiano 106/60’ pole cuttings growing at different densities in nurseries for 3 years. Different letters indicate significant differences $p \leq 0.05$ for a single variable

1.2 Sinuosity Index (SI)

A straight pole cutting has an SI of 1, and this indicates maximum straightness of the pole cutting; meanwhile numbers greater than 1 indicate sinuosity. In the 3 years measured, the straightest pole cuttings (lowest SI number) were found in the two plots with the widest spacings (1.2 m × 1.2 m and 1 m × 1 m) and the most sinuous pole cuttings, with the highest SI numbers, in the plot with the narrowest spacing ($p = 0.04$). However, no significant differences were found ($p = 0.1539$) between each of the years measured (Fig. 21.3).

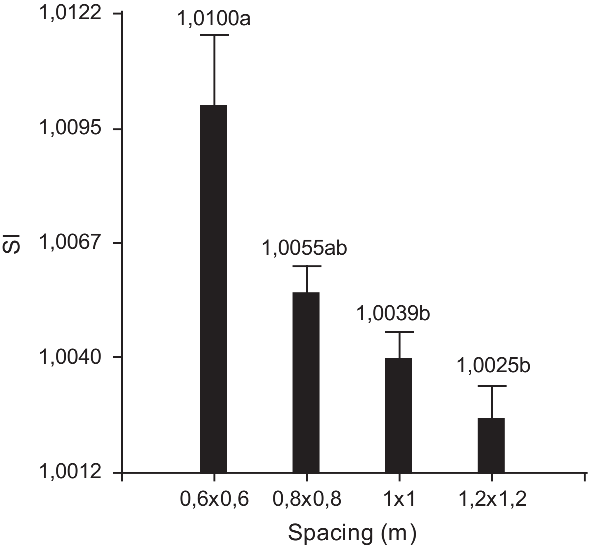

Fig. 21.3 Sinuosity index (SI) and standard error (SE) values for each spacing. Fisher's LSD (alpha = 0.05). Means with the same letter are not significantly different ($p \leq 0.05$)

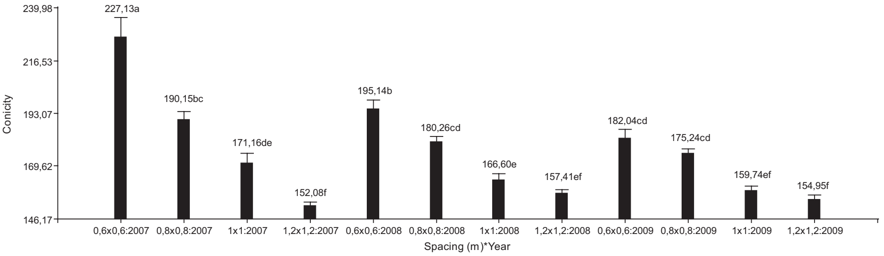

Fig. 21.4 Adjusted conicity means and standard errors for the distance*year interaction. Fisher's LSD (alpha = 0.05). Means with the same letter are not significantly different ($p \leq 0.05$)

1.3 Conicity or Stability Factor

In the third year of growth in nursery, the Ht (m) of the nine central pole cuttings and their DBH (m) during each year of growth were compared. This ratio was used as an indicator of tree stability against mechanical damage. The lower the height-to-diameter ratio of the pole cutting, the greater is the stability against mechanical damage (Durlo and Denardi 1998).

The years of growth and spacing between plants influenced the coefficients evaluated (highly significant interaction: $p \leq 0.001$). In the first, second and third year of the trial, the lowest height-to-diameter ratio (most conical trees) was obtained in the widest spacing (1.2 m × 1.2 m), followed by the third widest (1 × 1 m), while the highest numbers were recorded in the narrowest spacings (0.6 m × 0.6 m and 0.8 m × 0.8 m) (Fig. 21.4).

The findings show that the wider planting spacings correlated positively with straightness and stability and negatively with sinuosity and height-to-diameter ratio. According to Conaf-Infor (1997), Sanhueza (1998b), Ulloa and Villacura (2004) and Sotomayor (2009), in SPSs implemented in Chilean poplar plantations implanted with 2-year-old pole cuttings as propagating material, cattle are only introduced to the plantation in the fourth, fifth or sixth year, once the trees have reached a DBH that cannot be damaged by animals. This confirms the importance of the resistance of the propagation materials when implementing an SSP with cattle. In contrast, Larocque (1999), Ciria et al. (2002), Sixto et al. (2007) and Cañelas et al. (2012) showed that although the rate at which biomass is produced per unit area increases in the highest density plantations due to rapid crown closure and the complete occupation of the space, the mean DBH and the average number of branches and leaves are reduced. Moreover, the photosynthesis capacity of the plants is directly related to the leaf surface and is expressed as leaf area index (LAI) (Kozlowski et al. 1991; Leopold and Kriedemann 1975). As such, the pole cuttings that are the straightest, the most conical and therefore the most resistant against animal damage in a SPS are obtained in wider spacings.

1.4 Relationship Between Spacing and Accumulation of Biomass

The total average amount of biomass accumulated by each pole cutting was 3.2 times greater with 1.2 m × 1.2 m spacing, 2.6 times greater with 1 m × 1 m spacing and 1.4 times greater with 0.8 m × 0.8 m spacing, in relation to the narrowest spacing (0.6 m × 0.6 m) (Table 21.1). In the wider spacings, the greater availability of resources for each plant (sunlight, water and nutrients) may have determined the greater accumulation of total biomass as it meant the distribution of more biomass to the aerial parts (leaves and stems) than in the narrower spacings. Spacing had positive impact on radical biomass, which more than doubled in the two widest spacings: 1.93 vs. 4.10 and 4.96, respectively ($p \leq 0.05$). It is possible that the greater allocation of biomass to radicle development to the detriment of the aerial parts observed in the narrower spacings (Fig. 21.5) is associated with drought avoidance mechanisms, which include the reduction of the number of branches and leaves (Ciria et al. 2002).

Table 21.1 Biomass productivity values by plant (ha year^{-1}) for each spacing of *Populus deltoides* 'Australiano 106/60' at the third year of planting

Spacing	Biomass (kg plant^{-1})	Plant ha^{-1}	Biomass (kg ha^{-1})
0.6 m × 0.6 m	5,02 a	27.777	139.441
0.8 m × 0.8 m	6,82 a	15.625	106.563
1 m × 1 m	13,12 b	10.000	131.200
1.2 m × 1.2 m	16,14 c	6.944	112.083

Different letters indicate significant differences ($p \leq 0.05$)

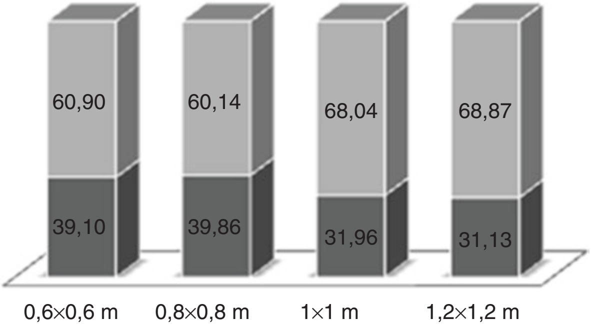

Fig. 21.5 Percentage of root (black bars) and stem (grey bars) in *Populus deltoides* 'Australiano 106/60' nurseries planted at different distances

Root development was recorded along the entire length of the buried portion of the pole cutting, 61% was placed in the first layer of soil, which belongs to the textural class of clay loamy, at an average depth of 25.6 cm located immediately below the black polyethylene mulch. Well-developed radicle rooting systems allow the plant to maintain high water potential (Turner 1979). These results are consistent with the optimal biomass allocation theory proposed by Thornley (1969), which suggests that plants preferentially allocate biomass to the plant organ involved in capturing the most limited resource, and with Tschaplinski et al. (1998), who, for moderate drought conditions, reported a greater drought resistance of clones, which allocate a greater proportion of carbon to the roots. This enables us to understand how aerial and underground biomass of the poplar pole cuttings accumulate and partition at different spacing.

1.5 Leaf Area Index (LAI) and Specific Leaf Area (SLA)

LAI is the total leaf area per unit of ground surface area (Perry 1994; Cherry et al. 1998; Smethurst et al. 2003), and it is considered a good indicator of the capacity of the crown to absorb photosynthetic active radiation (Perry 1994), one of the most useful parameters in the characterisation of vegetation. Its determination is of great importance in studies related to growth and development given that the carbohydrates distributed to the different organs are synthesised in the leaves. Meanwhile, the SLA is closely tied to plant growth and is considered one of the key elements of plant competition (Reich et al. 1992) at both individual and ecosystem level, with this variable being responsible for up to 80% of the differences in growth between different species (Villar et al. 2004).

The productivity of the pole cuttings was greater in the third year across all four planting spacings analysed ($p \leq 0.05$) (Table 21.2). LAI ($p = 0.6581$), AFE ($p = 0.2043$), dry weight of the blade ($p = 0.4217$) and petiole length of the crown leaves ($p = 0.4615$) did not show any significant differences. However, LAI of the leaf blades from the upper third of the pole cuttings doubled that of the central third and tripled that of the lower third of the crown ($p = 0.0001$) (Fig. 21.6).

Table 21.2 Mean (standard deviation) of the structural and microenvironmental parameters derived from hemispherical photographs taken at 2, 5 and 8 m above canopy height, in March, 2009, at each spacing tested in plots of *Populus deltoides* 'Australiano 106/60'

Spacing (m × m)	0.6 × 0.6	0.8 × 0.8	1 × 1	1.2 × 1.2
Sunflecks (minutes)	10.36 (1.45)	12.56 (3.4)	11.34 (2.48)	12.95 (2.74)
ISF (%)	0.45 (0.03)	0.46 (0.02)	0.49 (0.03)	0.49 (0.03)
DSF (%)	0.48 (0.03)	0.51 (0.03)	0.52 (0.03)	0.52 (0.03)
GSF (%)	0.48 (0.03)	0.50 (0.03)	0.51 (0.03)	0.52 (0.03)
Par (%)	2.12 (0.14)	2.01 (0.11)	1.96 (0.11)	1.93 (0.11)
GndCover (%)	0.21 (0.08)	0.14 (0.14)	0.04 (0.05)	0.05 (0.07)
LAI effective (m^2 m^{-2})	1.14 (0.13)	1.14 (0.09)	1.08 (0.10)	1.07 (0.13)
Vis sky (%)	0.31 (0.03)	0.31 (0.02)	0.33 (0.02)	0.33 (0.04)
LAI Dev (%)	0.57 (0.12)	0.77 (0.11)	0.68 (0.18)	0.70 (0.17)

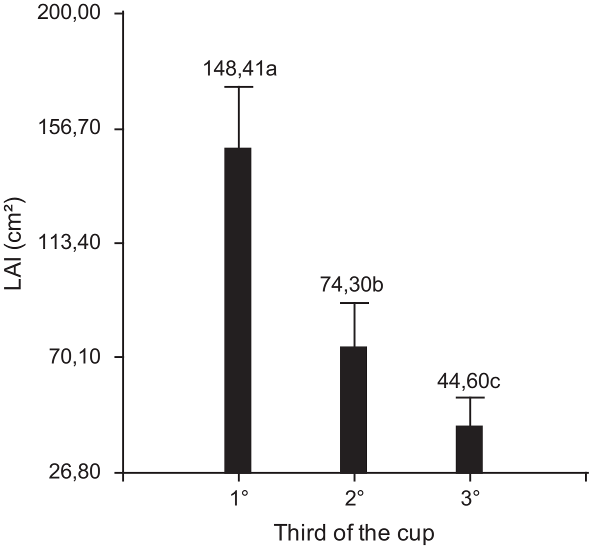

Fig. 21.6 LAI (± standard deviation) in pole cutting *Populus deltoides* 'Australiano 106/60', planted at different distances, at different height of the cup, at third year of age. Means with the same letter are not significantly different ($p \leq 0.05$)

The weight of the leaves and the length of petioles in the upper part of the crown were higher ($p = 0.0001$) than in the lower third (Fig. 21.7).

In the present study, the accumulation of biomass at the different planting spacing analysed (Table 21.4) was associated with SLA and the length of petioles in the upper third of the crown. The SLA presented significant differences across the three thirds of the crown; the lowest value was found in the upper third and the highest value in the lower third ($p = 0.0101$) (Fig. 21.8).

Niinemets et al. (2004) believe that leaves with longer petioles and larger leaves intercept light more efficiently. In the trial, the total biomass of the pole cuttings, leaf biomass and SLA decreased significantly as planting density increased (Table 21.5). Similarly, studies carried out by Larocque (1999) on a *P. deltoids x nigra hybrid*

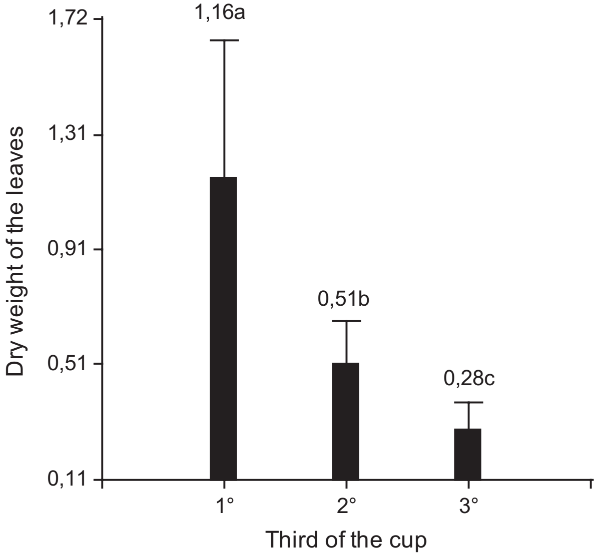

Fig. 21.7 Dry weight of the leaves (± standard deviation) in pole cutting *Populus deltoides* 'Australiano 106/60', at third year of age, at different height of the cup, planted at different distances. Means with the same letter are not significantly different ($p \leq 0.05$)

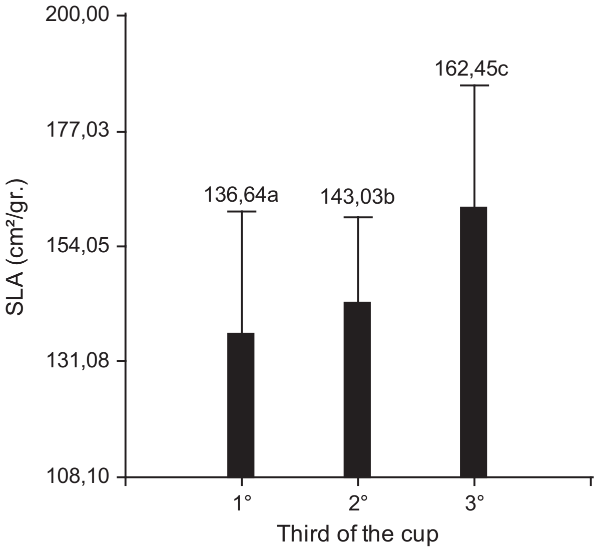

Fig. 21.8 SLA (± standard deviation) of the leaves in pole cutting *Populus deltoides* 'Australiano 106/60', at third year of age, at different height of the cup, planted at different distances. Means with the same letter are not significantly different ($p > 0.05$)

found that foliar biomass decreased significantly when planting density increased. In their trials of poplars for bioenergy, Cañelas et al. (2012) reported that, at the end of the first year, biomass production differed significantly between sites and planting densities. After the first year of growth, the biomass production per unit of ground area increased exponentially with density. However, after the third year, at the end of the first rotation, no significant differences were found in growth, and, just as what happened in our case, the highest biomass production per unit of ground area was achieved in the highest planting densities. In part, this would explain the relationship between the structure with the light microenvironment on the variables DBH and Ht at each spacing tested in the nursery. The findings obtained are also related to the findings of Corcuera et al. (2005): less competition in the nursery for light, water and nutrients directly affects diameter, height and total biomass yield.

1.6 Characterisation of the Canopy and Light Microenvironment Using Hemispheric Photography

In order to characterise the heterogeneity of the light received by the nursery tree canopy and the light microenvironment within the plots, at the end of summer, 2009, 72 hemispherical photos were taken, 3 per plot centre, at 2 m, 5 m and 8 m above ground level. All photos were taken early morning and late evening to ensure uniform lighting of the sky (diffuse light). The field equipment used was a fisheye hemispheric lens. The variables were calculated using the program HemiView 2.1 (Delta-T Devices 1999). Eight azimuth divisions and 15 zenith divisions were used for the calculations and distribution of diffuse radiation.

The calculated variables were Sunflecks, which are the result of many small discontinuities in the tree canopy (Pearcy 1990): ISF, the amount of indirect or diffuse solar radiation that reaches the forest floor; DSF, the amount of direct solar radiation that reaches the forest floor; and GSF, the total amount of solar radiation (direct + diffuse) under the forest canopy. The ISF, DSF and GSF indexes are used as a means of expressing the relative contribution of indirect, direct and total photosynthetically active radiation in the understorey in relation to the over-storey (Anderson 1964). GndCover estimates the fraction of ground covered by the tree canopy. Their values range from 0 (when the sky is fully visible) to 1 (when the sky is completely covered or dark). PAR is the total photosynthetically active radiation beneath and above the tree canopy. Effective LAI is the leaf area index. Vis Sky indicates the fraction of the sky that is visible, the proportion of unobstructed sky. LAI dev measures the uniformity of the distribution of the sky visible through the canopy or the uniformity of the distribution of light reaching the ground. Its values generally range from 0 upwards. Values equal or very close to 0 mean that the sky is uniformly clear and higher values mean that the sky is more uniformly obstructed. ISF (0.001), GSF ($p = 0.035$) and PAR ($p = 0.04$) varied significantly according to spacing; however, upon analysing the vertical profile of the nursery, no significant differences were detected across the three canopy heights analysed ($p > 0.05$) (Table 21.2).

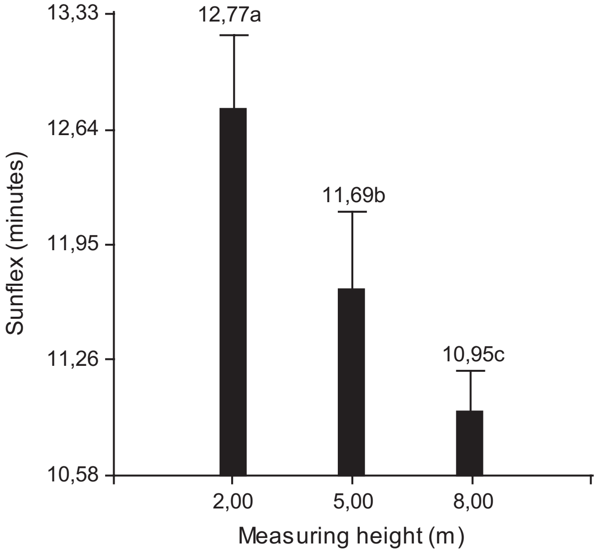

Fig. 21.9 Average Sunflecks duration registered at 2, 5 and 8 m height within the plots and their standard deviation

Table 21.3 Mean (standard deviation) of the structural and microenvironmental parameters derived from hemispherical photographs taken in March 2009, at the different *Populus deltoides* 'Australiano 106/60' planting spacings at each height measured

Variable	Measuring height		
	2 m	5 m	8 m
ISF	0,47 (0,03)	0,48 (0,03)	0,47 (0,03)
DSF	0,50 (0,04)	0,51 (0,03)	0,51 (0,04)
GSF	0,50 (0,03)	0,50 (0,03)	0,50 (0,04)
GndCover	0,11 (0,12)	0,11 (0,11)	0,12 (0,12)
LAI effective	1,11 (0,11)	1,10 (0,11)	1,10 (0,12)
PAR	2,02 (0,15)	2,00 (0,12)	2,00 (0,13)
Vis sky	0,32 (0,02)	0,32 (0,03)	0,32 (0,03)
LAI Dev	0,70 (0,16)	0,69 (0,16)	0,65 (0,17)

Sunflecks, however, did not vary with the spacing ($p > 0.053$), and upon analysing the vertical profile of the nursery, significant differences were found in the values recorded at 2, 5 and 8 m in height ($p = 0.036$) (Fig. 21.9).

DSF and Vis Sky increased in the wider spacings, with no variation between treatments (Table 21.2) or the three canopy heights analysed (Table 2.3). Conversely, GndCover and effective LAI decreased in the widest spacings without presenting significant differences (Table 21.2), as did the values recorded at the three heights measured on the plots (Tables 21.3 and 21.4).

Table 21.4 Pairwise correlation coefficients and their associated probabilities with the average productive, dasometric, morphological and microenvironmental variables of the four planting spacings analysed in the *Populus deltoides* 'Australiano106/60' nursery at the third year of age

	Spacing	Total biomass	DBH (cm)	Ht (m)	Straightness	Conicity	ISF	DSF	GSF	LAI dev	AFE
Total biomass	**0,98** ($p = 0,02$)										
DBH (cm)	**0,98** ($p = 0,02$)	**0,99** ($p = 0,01$)									
Ht (m)	**0,98** ($p = 0,02$)	**1** ($p < 0,0001$)	**0,99** ($p = 0,01$)								
Volume		**0,97** (0,03)		**0,97** (0,03)							
Straightness	`		` **– 0,97** ($p = 0,03$)	` **– 0,98** ($p = 0,02$)							
Conicity	` **– 0,99** ($p = 0,01$)	` **– 0,97** ($p = 0,04$)	`**–0,98** ($p = 0,03$)	`**–0,97** ($p = 0,04$)	**0,96** ($p = 0,04$)						
ISF		**0,99** ($p = 0,001$)	**0,99** ($p = 0,001$)	**0,98** ($p = 0,02$)	´**0,97** (0,03)						
DSF	**0,95** (0,05)	**0,96** (0,04)	**0,99** (0,01)	**0,96** (0,04)		**–0,97** ($p = 0,03$)					
GSF	**0,95** ($p = 0,05$)	**0,96** ($p = 0,04$)	**0,99** ($p = 0,01$)	**0,96** ($p = 0,04$)	`	`**–0,97** ($p = 0,03$)	**0,97** ($p = 0,03$)	**1** ($p < 0,0001$)	**0,99** ($p = 0,01$)		
PAR	´**–0,95** ($p = 0,05$)	´**–0,95** ($p = 0,05$)	**–0,98** ($p = 0,01$)	`**–0,95** ($p = 0,05$)		**0,97** ($p = 0,03$)	`**–0,97** ($p = 0,03$)	`**–1** ($p = 0,003$)	`**–1** ($p = 0,003$)		
Gndcover		´**–0,96** ($p = 0,04$)	`**–0,97** ($p = 0,03$)	`**–0,97** ($p = 0,03$)	**0,99** ($p = 0,01$)	**0,98** ($p = 0,03$)	`**–0,99** ($p = 0,02$)	`**–0,94** ($p = 0,06$)			
Vis sky							**0,95** ($p = 0,05$)				
AFE										**0,95** ($p = 0,05$)	
Leaf weight										´	´**–0,95** ($p = 0,05$)

The table only shows the statistically significant correlations ($p \leq 0.05$)

The results obtained confirmed the hypotheses. Thus, the widest spacing presented a positive response in DBH and Ht, as well as a greater proportion of direct and total solar radiation on the ground of the nursery and the best height-to-diameter ratios of the four spacings analysed. The fraction of ground covered by the forest canopy (GndCover Index) showed a positive correlation with the sinuosity index and the height-to-diameter ratio and a negative correlation with the total biomass, DBH and Ht. The accumulation and partition of biomass, the size of the pole cuttings, the straightness and height-to-diameter ratio, the leaf area index and the specific leaf area in the *P. deltoides* 'Australiano 106/60' nursery were directly related to spacing. These microenvironments were characterised by a higher proportion of direct and total solar radiation and less photosynthetically active radiation .

2 The Effect of Grazing on Poplar Pole Cuttings of Different Ages in Silvopastoral Systems

There are records of the introduction of livestock in the third year with the use of 1- and 2-year-old rooted pole cuttings (Suárez and Borodowski 1999) or 2-year-old unrooted pole cuttings (Ulloa and Villacura 2005). The diameters and root biomass that 1-, 2- and 3-year-old *P. deltoides* unrooted pole cuttings can reach (Casaubón 2003) may allow the introduction of cattle to SPSs without the need to protect each tree individually, thus minimising the costs of establishing the system. We predict that:

In an SPS of *Populus deltoides* 'Australiano 106/60':

1. The damage caused to the trees by cattle is inversely related to the age and size of the propagation material and the characteristics of the natural grassland (availability of DM and its floristic composition, abundance and nutritional value).
2. The tender twigs and leaves on trees are a good complement to livestock feed.

The aim of this trial is to determine the effect of the size and/or age of the pole cuttings on the growth of the tree component and the sensitivity of the trees to the damage caused by the grazing of cattle in an SPS of *P. deltoides* 'Australiano 106/60'.

This study was carried out in an SPS of *P. deltoides* 'Australiano 106/60' with an area of 2.5 ha, planted with 1-, 2- and 3-year-old pole cuttings with 6 × 6 m spacing between each row and each plant in an endyked area of the fourth section of the Islands of the Lower Delta of the Paraná River (Table 21.5).

The availability of water was ensured by installing a pumping system that facilitated the inflow of water during times of scarcity and the discharge in times of excess water after heavy rainfall. This system allowed the water to flow along the channels and drainage ditches and prevented it from becoming stagnant. One (PC1)-, two (PC2)- and three (PC3)-year-old *P. deltoides* 'Australiano 106/60' pole cuttings were used as propagation materials.

Table 21.5 Physicochemical characteristics of soil ($n = 6$) and their standard deviations according to the test carried out in an endyked area of the National Institute of Agricultural Technology (INTA) Paraná Delta Agricultural Experimental Station

Cap	1	2	3	4
Depth	0–15	15–28	28–53	>53
Textural class	Clay loam	Clay loam	Loam	Loam
pH	4,28 ± 0,22	4,9 ± 0,15	4,73 ± 0,12	4,72 ± 0,08
Organic material (%)	48,36 ± 6,65	28,96 ± 5,11	1,8 ± 0,34	0,81 ± 0,33
Organic carbon (%)	28,05 ± 3,86	16,8 ± 2,96	1,04 ± 0,2	0,47 ± 0,19
Organic nitrogen (%)	1,35 ± 0,17	1,15 ± 0,09	0,1 ± 0,02	0,05 ± 0,02
Assimilable phosphorus (ppm)	17,3 ± 16,06	12,35 ± 13,97	1,43 ± 0,49	6,62 ± 7,15
Cation exchange capacity (meq/%)	47,8 ± 9,91	36,77 ± 7,17	19,23 ± 3,63	11,25 ± 1,64
Saturation (%)	51,37 ± 3,99	52,33 ± 4,34	62,07 ± 2,83	65,55 ± 2,79
Sodium exchange (%)	0,72 ± 0,22	0,93 ± 0,41	2,03 ± 0,37	4,18 ± 1,47
Calcium	17,5 ± 3,51	13,27 ± 2,1	7,4 ± 1,57	4,4 ± 0,65
Magnesium	5,67 ± 0,85	4,85 ± 0,83	3,8 ± 0,64	2,27 ± 0,49
Potassium	0,77 ± 0,08	0,45 ± 0,18	0,3 ± 0,06	0,25 ± 0,05
Sodium	0,35 ± 0,15	0,33 ± 0,15	0,42 ± 0,16	0,45 ± 0,16

A randomised complete block design (RCBD) was used with six replications across the ground height and availability of water gradients. The treatments used were T1, control, with no animals introduced, and T2, grazing with 18 breeding heifers (Aberdeen Angus breed, weighing approximately 300 kg), with an instantaneous grazing pressure of 12 animals per hectare. Grazing started 18 months after planting. Three propagation materials were used in each main treatment (T1 and T2): PC1, PC2 and PC3. Each lot used in the trial consisted of six plots (replications) measuring 0.25 ha each. Sixty-four (rootless) 1-, 2- and 3-year-old pole cuttings from a single clone were planted at random in these plots (roughly balanced, with between 21 and 22 pole cuttings of each age per plot) with 6 × 6 m spacing between each plant. The sizes of the pole cuttings at the time of planting were as follows: DBH (cm) PC1, 2.8 ± 0.4; PC2, 4.6 ± 0.88; and PC3, 5.1 ± 1.28 and Ht (m) PC1, 4.25 ± 0.43; PC2, 7.30 ± 0.96; and PC3, 7.84 ± 1.32.

The DBH and Ht of each live tree were measured annually for the first 3 years. Three trees of 3 years old were selected in each block, one from PC1, one from PC2 and one from PC3, giving a total average of 18 trees (3 × 6). Plants heavily damaged by cattle were not analysed. All propagation materials used yielded a 100% success rate in rooting. Three years after the start of the trial, the greatest increase in DBH and Ht was found in the pole cuttings that were 1 year old at the time of planting (DBH 1.94 cm year^{-1} and Ht 0.92 cm year^{-1}) followed by the pole cuttings that were 2 years old at the time of planting (DBH 1.55 cm/year^{-1} and Ht 0.34 cm year^{-1}) and finally the pole cuttings that were 3 years old at the time of planting (DBH 1.12 cm year^{-1} and Ht 0.18 cm year^{-1}). However, in the third year following planting, the trees from PC1 had lower a DBH and Ht ($p <= 0.05$) than those from PC2 and PC3, and no difference was found between the latter two ($p > 0.05$) (Table 21.6).

Table 21.6 The main average dasometric parameters (± standard deviation) recorded for the one (PC1)-, two (PC2)- and three (PC3)-year-old *Populus deltoides* 'Australiano 106/60' pole cuttings in the third year of growth after planting

Tree	N	DBH(cm)	BA (mm^2ha^{-1})	Ht (m)	HD (m)
PC1	6	13,16 (1,33)b	0,103 (0,01)	11,59 (1,33)b	12,62 (1,03)
PC2	6	14,94 (1,53)a	0,117 (0,01)	12,85 (0,59)a	13,32 (0,44)
PC3	6	14,62 (0,84)a	0,115 (0,01)	12,99 (0,90)a	13,62 (0,72)

DBH Diameter 1.3 m above ground, *BA* basal area, *Ht* total height, *HD* dominant height of PC1, PC2 and PC3 at year 3 after planting
Means with the same letter are not significantly different ($p <= 0.05$)

Although the rooting success rate for PC1, PC2 and PC3 was 100%, the DBH and Ht of the trees from PC1 increased faster than that of those from PC2 and PC3 during the first year of growth. However, by the third year, trees from PC2 and PC3 showed a significantly higher DBH and Ht than those from PC1. A similar situation was described by Casaubón et al. (2006) when comparing the dasometric growth of cuttings (C) with those of PC1 and PC2 *P. deltoides* '106/60'. However, in the same trial, Casaubon et al. (2011) found that, in the 8th year of planting, the trees from PC2 had a greater DBH and Ht than those from PC1 and C. The greater accumulation of biomass in the pole cuttings in comparison with E may be the cause of successful rooting of these materials as mentioned by Nanda et al. (1971).

2.1 The Impact of Cattle on the Pole Cuttings (PC1, PC2 and PC3)

The percentage of plants damaged (damaged bark) by the cattle (15 days grazing) was evaluated in two occasions (December 2007 and January 2008). In the first occasion, all the thin branches and tender leaves reached by animals (at a height of under 2 m) were consumed in 100% of the cases. There was also damage to the trees in the form of bark stripping at animal height. The damage to the bark was detected after 10 days of grazing. In both occasions, the percentage of damaged plants was 11% of the total tree planted (Table 21.7). These differences (damaged pole cuttings vs. pole cuttings with no damage to the shaft in plots that received the 'livestock entry' treatment) were observed for all propagation materials used (Chi2:85.41; Gl:1; $p < 0.05$). On the second occasion, no browsing was recorded.

The intensity of the damage was correlated with the DBH (Fig. 21.10) and the age of the pole cuttings (Fig. 21.11). The effect of bark stripping on the mean DBH of the trees did not differ between PC1, PC2 and PC3 ($p = 0.5446$). However, the plants stripped by the animals had a significantly lower ($p < 0.001$) mean DBH (4.36 cm) than the undamaged ones (5.72 cm). The 1-year-old pole cuttings (PC1) (4.42 cm) had a lower DBH than the 2-year-old (PC2) (5.37 cm) and 3-year-old (5.65 cm) ($p < 0.001$) pole cuttings. In the damaged plots, plants from 1-year-old

Table 21.7 Amount and type of damage caused to *Populus deltoides* 'Australiano 106/60' trees from pole cuttings of 1 (PC1), 2 (PC2) and 3 (PC3) years of age on the two occasions that cattle were introduced to the silvopastoral trial plots

Treated plots(6)	Number of total plants	Number of plant with damaged bark	Number of browsing plants	Number of broken plants	Number of plants lying down
Income of animals in December 2007					
PC 1	128	40	34	0	0
PC 2	130	13	4	0	0
PC 3	126	8	19	0	0
Income of animals in January 2008					
PC 1	128	23	0	0	0
PC 2	126	0	0	0	0
PC 3	130	1	0	0	0

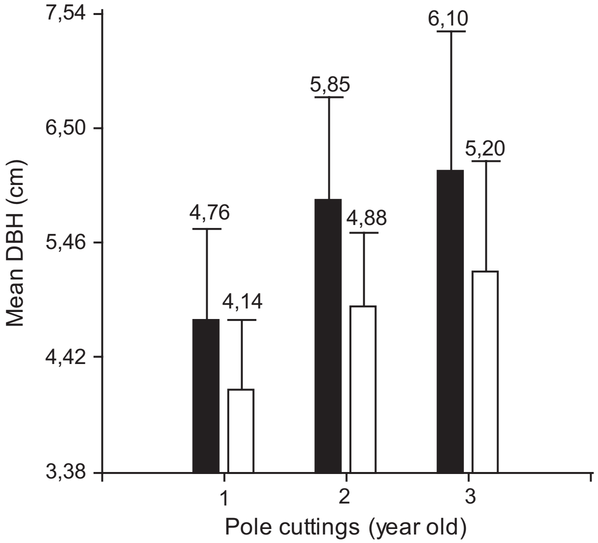

Fig. 21.10 Variation of the mean DBH of the *Populus deltoides* 'Australiano 106/60' plants from 1 (PC1)-, 2 (PC2)- and 3 (PC3)-year-old pole cuttings with bark (black bars) and that have had their bark stripped by cattle (white bars)

pole cuttings were more severely stripped by the livestock than those from 2- and 3-year-old pole cuttings ($p < 0.01$) (Fig. 21.11). Damage caused by Aberdeen Angus cattle to the bark of *Populus deltoides* 'Australiano 106/60' trees from pole cuttings of 1 (PC1), 2 (PC2) and 3 (PC3) years of age 10 days after their introduction to the silvopastoral trial is clearly shown in Fig. 21.12.

The plantation materials used in this study (conventional Delta nurseries with 0.4 m × 0.8 m spacing between strains) were affected by the cattle, mainly during

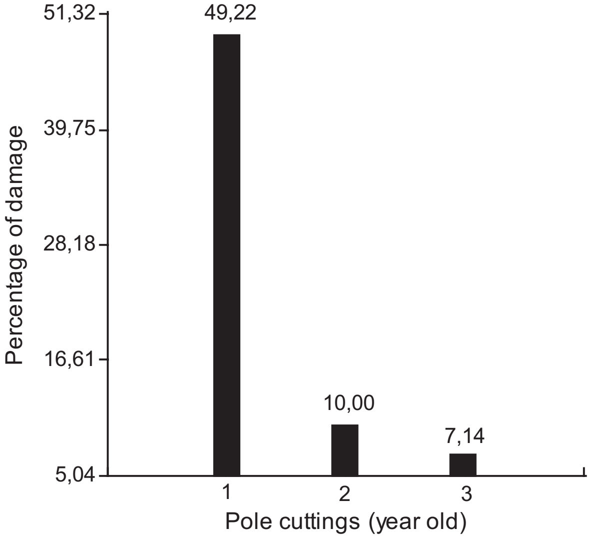

Fig. 21.11 Percentage of damage to *Populus deltoides* 'Australiano 106/60' trees from 1- (PC1), 2- (PC2) and 3 (PC3)-year-old pole cuttings 18 months after planting following cattle grazing in a silvopastoral system in the Delta of the Paraná River

Fig. 21.12 Damage caused by Aberdeen Angus cattle to the bark of *Populus deltoides* 'Australiano 106/60' trees from pole cuttings of 1 (PC1), 2 (PC2) and 3 (PC3) years of age 10 days after their introduction to the silvopastoral trial

the first grazing period. These had been designed to produce linear metres of pole guides per unit of ground area (generally used to produce cuttings) and therefore no reaching resistant pole cuttings with a minimum DBH of 6 cm (as analysed in the first trial). These findings are consistent with those of Somarriba (1997), who found that the damage caused to young plants by cattle may lead to decreased shaft quality because of bark stripping and even to the death of some trees, as occurred in this trial. However, it is not known whether the stripping of plants with diameters less than 6 cm was due to the greater palatability of the bark of 1-year-old pole cuttings or due to the cattle having trouble stripping larger diameter shafts. The findings confirm the second hypothesis that the start of the bark stripping by cattle grazing in a poplar SPS is inversely related to the diameter and age of the propagation material.

2.2 *Biomass in Trees*

The total biomass (aerial and underground) of one average tree from each of the three propagation materials PC1, PC2 and PC3 in each replication was measured after 3 years of the trial installation. The dry weight values for each compartment of biomass were calculated using dimensional analysis (Whittaker and Woodwell 1968).

The total dry weight of PC2 and PC3 was greater ($p < =0.05$). This was due to a greater proportion of shaft (and bark in G2) and thick roots (>5 cm) (Table 21.8). The greatest partitioning to root occurred in PC3 with respect to PC1 ($p < 0.05$), and trees from PC1 presented less radicle development (Table 21.9).

Table 21.8 Total dry weight (kg) and dry weight per compartment (± standard deviation) of average 3-year-old *Populus deltoides* 'Australiano 106/60' trees from PC1, PC2 and PC3, which were not damaged by the cattle

Tree	PC1($n = 6$)	PC2 ($n = 6$)	PC3 ($n = 6$)
Stems w/b	20,38 (5,57)b	27,14 (9,23)a	26,70 (7,76)a
Bark	3,35 (0,80)b	4,58 (1,57)a	4,48 (1,27)ab
Branches >1 cm	8,17 (3,76)a	9,28 (4,32)a	8,43 (2,81)a
Branches <1 cm	2,34 (1,32)a	1,98 (0,94)a	3,21 (1,95)a
Leaves	4,10 (0,97)a	4,36 (1,81)a	4,83 (1,19)a
Thick roots (>5 cm)	2,89 (1,77)c	7,47 (3,24)b	12,15 (3,43)a
Medium roots (>1 cm)	8,71 (2,15)a	9,30 (4,02)a	10,18 (2,38)a
Fine roots (<1 cm)	0,67 (0,34)a	1,41 (0,68)a	1,41 (0,53)a
Total	50,64 (9,89)b	65,57 (17,73)a	73,80 (8,21)a

Means with the same letter are not significantly different ($p < =0.05$) between treatments for the same component

Table 21.9 Total dry weight of root, stem and root/stem ratio (± standard deviation) of 3-year-old *Australian 106/60 Populus deltoides* trees from pole cuttings of 1 (PC1), 2 (PC2) and 3 (PC3) years of age

Dry weight (kgr.)				
Tree	*N*	Root	Shoot	Root/Shoot
PC1	6	12,05 (1,03)b	38,59 (9,49)b	0,33 (0,07)b
PC2	6	18,18 (4,04)a	47,39 (14,86)ab	0,40 (0,11)ab
PC3	6	23,74 (4,90)a	50,07 (6,90)a	0,48 (0,13)a

Means with the same letter are not significantly different ($p <= 0.05$)

2.2.1 Forage Value of Poplar Leaves

Eighteen 50-gramme samples of leaves were taken in October and December 2009 and at the end of March 2010 from three trees per plot from pole cuttings of different ages. The wet weight (WW) was determined, and the samples were then put in a stove at 60 °C and dried to a constant weight, and their DM (dry matter), ADF (acid detergent fibre), NDF (neutral detergent fibre) and GP (gross protein) were determined. ED (estimated digestibility) values were calculated using the following formula: 88.9 − (0.779x% average ADF) (Ustarroz 1995). The content of macronutrients Ca (calcium), Mg (magnesium), P (phosphorus) and K (potassium) was determined. The quality of the poplar leaves did not vary between trees originating from pole cuttings of different ages ($p > 0.05$), and they did vary according to the time of harvest ($p < 0.05$) (Table 21.6). The % of DM increased between October and March ($p < 0.05$) (Table 21.10). The highest ADF values ($p < 0.05$) were found in leaf samples collected in the field between October and in March, compared to the lowest ED values ($p < 0.05$), which were found in December. Meanwhile, while the highest NDF values ($p < 0.05$) were found in the month of March, CP was significantly higher ($p < 0.05$) in October.

The macronutrients content of the poplar leaves had no relation to the age of the pole cutting from which the trees were planted and did vary according to the time of year ($p < 0.05$) (Table 21.11). The concentration of K and P was higher ($p < 0.05$) in October and the Mg concentration was higher in March. Meanwhile, the highest concentration of Ca ($p < 0.05$) was found in the month of December.

Ibrahim et al. (2006) stated that the combination of grassland and the tender leaves and twigs of fodder trees increase the nutritional value of animal diet, while

Table 21.10 Average values (± standard deviation) for dry matter (DM), acid detergent fibre (ADF), estimated digestibility (ED), neutral detergent fibre (NDF) and gross protein (GP) expressed as a percentage (%) in *Populus deltoides* 'Australiano 106/60' leaves from 1-, 2- and 3-year-old pole cuttings from the 2009/2010 vegetative period

Month	DM%	FDA %	Digestibility %	FDN %	GP %
October	20,17 ± 2,55^{a}	32,31 ± 5,05^{a}	63,73 ± 3,94^{b}	50,90 ± 5,89^{ab}	30,26 ± 2,07^{a}
December	36,59 ± 1,04^{b}	27,65 ± 3,39^{b}	67,36 ± 2,64^{a}	48,71 ± 2,69^{b}	15,71 ± 2,44^{b}
March	42,3 ± 1,05^{c}	34,50 ± 3,89^{a}	62,02 ± 3,03^{b}	53,31 ± 2,47^{a}	16,52 ± 2,01^{b}

Different letters indicate significant differences ($p <= 0.05$) between months

Table 21.11 Macronutrients concentrations (Ca, Mg, K and P) (± standard deviation) in *Populus deltoides* 'Australiano 106/60' leaves during the vegetative period

Month	Ca% (gr/100gr)	Mg % (gr/100gr)	K % (gr/100gr)	P (mg/kg)
October	0,69 ± 0,17^{b}	0,49 ± 0,10^{ab}	1,95 ± 0,24^{a}	500 ± 123,34^{a}
December	1,09 ± 0,37^{a}	0,45 ± 0,14^{b}	0,96 ± 0,31^{b}	183,64 ± 21,49^{b}
March	0,76 ± 0,23^{b}	0,56 ± 0,10^{a}	1,07 ± 0,33^{b}	176,94 ± 23,93^{b}

Different letters indicate significant differences ($p <= 0.05$) between months

Fig. 21.13 Aberdeen Angus heifers eating leaves and tender branches of *Populus deltoides* product of a pruning done in spring

the fallen leaves from trees stimulate the nutrient cycle, protect the soil and improve its fertility. Meanwhile, Hernández and Benavides (1995), Rossi et al. (2005), Mead (2009), Carou et al. (2010) and Thomas (2011) found that the young branches and leaves of woody species such as the poplar showed high forage potential due to their nutritional qualities and palatability. These can be used as good feeding supplements in an SPS, improve grazing cattle diet and contribute forage volume in times of shortage. Ball et al. (2005) report that in New Zealand, the pruning of poplars is encouraged to produce young branches and leaves that are used as alternative forage. In the Delta of the Paraná River, Casaubon et al. (2005b) studied the ideal time of year and intensity for pruning and concluded that spring pruning minimised the growth of epicormic shoots on tree shafts.

Furthermore, the preference of cattle for poplar tender leaves and branches from systematic pruning of the shaft is well-known. However, for 2 consecutive years in field, it was found that this preference did not remain constant throughout the tree's vegetative period being greater in spring until early summer and disappeared during mid-summer and autumn (Fig. 21.13).

Supporting this, in December 2008 as part of this study, we found that the nutritional value of the poplar leaves was higher than grassland. From a practical point of view, in the implementation of SPSs, the damage caused by livestock to 100% of the tender leaves and branches could be avoided by systematic pruning in spring to eliminate all epicormic shoots that appear in the pole cutting after planting. Although

Cameron (2003), Kemp et al. (2003) and Sulaiman (2006) found that, in the summer, the nutritional value of poplar leaves is equal or greater than grassland (which would explain the affinity of the cattle for these leaves). In our case, the highest average GP values ($p < 0.05$) were found in tender spring leaves, practically doubling the values recorded at the start of the summer. In contrast, ED values increased in December ($p < 0.05$) and decreased in March ($p < 0.05$), when the roughness of the leaf increases (Heady and Child 1994). The nutritional values of poplar leaves and tender shoots in October, December and March were linked to heifer higher preference during spring and early summer.

The lack of livestock preference for such leaves in February was related to poplar tender leaf nutritional value and forage quality in spring and early summer and with quality loss of grasses at that time of year at reproductive stage. In the absence of other restrictions, animals in search of food choose the type of food and how long to stay at the same spot based on the amount of energy they obtain from it, the energy they use and the time they spend on the process (Pyke et al. 1977). Analyses of macronutrient content in poplar leaves also showed that while the greatest availability of K and P was in October, the greatest availability of Ca was in December and the greatest availability of Mg was in March; these values are consistent with those found by Carou et al. (2010) in the leaves of other poplar clones. It is also necessary to carry out additional studies on other compounds such as tannins, which can modify palatability according to season (Leslie et al. 1984). Our study found that, although poplar leaves have greater nutritional values than grasses in March, these lose their palatability (the cattle no longer consume them). It is likely that, in addition to the roughness of the leaf at this time of year, anti-nutritional effects may occur due to a higher presence of tannins or phenolic compounds than is usually found in their diet (Mole and Waterman 1987) which could reduce the digestibility of the protein (González Hernández et al. 1999). This confirms the third hypothesis that poplar leaves are a good complement to livestock diet in spring and early summer.

2.2.2 Aerial Biomass in the Understorey

A study of the composition of the spontaneous vegetation in the silvopastoral system was carried out before the entry of cattle (January 2008), 10 days after animal left plots (February 2008), and from September 2008 to August 2009 to describe the initial situation and its subsequent evolution. Sixty samples using 0.25 m^2 quadrats (ten samples per plot) were taken at random to measure abundance coverage using the Braun-Blanquet scale (1979). The numerical species richness of each sample was calculated (Krebs 1989). Diversity indexes offer an alternative way of describing relationships between species abundance in the community and can also be used for comparative purposes (Fernández 1997).

The initial availability of biomass of the grassland was estimated at 4403 (±471.75) kg of DM ha^{-1}, and the remainder following the removal of the animals was estimated at 2404 (±421.17) kg of DM ha^{-1}, 55% less due to the grazing of the cattle. Although these differences were significant ($p = 0.002$), when the cattle were

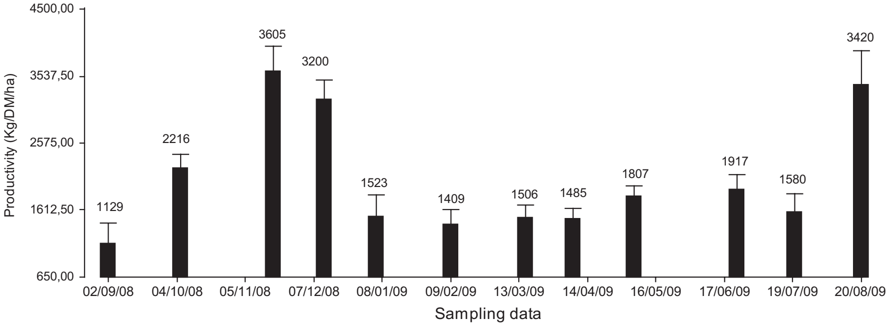

Fig. 21.14 Average monthly productivity ($n = 6$) (kg of DM ha^{-1}) of natural grassland regrowth in September 2008 and August 2009, in an SPS of *Populus deltoides* 'Australiano 106/60' in the Lower Delta of the Paraná River

removed, the forage available in the undamaged plots was 53% and the damaged plots of 41% without differences ($p = 0.84$). Subsequently, the average regrowth productivity in September 2008 and August 2009 (without grazing) was 2066 kg of DM ha^{-1}. The highest productivity values were recorded during winter (2012 kg ha^{-1}) and spring (3007 kg ha^{-1}), while the lowest values were recorded during autumn (1646 kg ha^{-1}) and summer (1401 kg ha^{-1}) (Fig. 21.14).

2.2.3 Relative Grassland Composition and Diversity

There was a decrease in the percentage of coverage of *Cirsium vulgare*, *Conyza bonariensis*, *Carex riparia*, *Cyperus* spp. and *Phalaris angusta* and an increase in bare soil and dry grass (Table 21.12).

After the animals were removed from the plots, the average wealth of the species composing the grassland and the Shannon Index immediately decreased in value. However, 12 months after the removal of the cattle, these values had increased to surpass the average wealth prior to grazing. Conversely, the Jaccard Index values showed a slow and gradual decline over time (Table 21.13).

The differences in plots with and without damage shown in Table 21.14 were not significant for genera *Carex* ($p = 0.5298$), *Conyza* ($p = 0.0603$) and *Polygonum* ($p = 0.2202$) and the dry grass component ($p = 0.1171$). However, they were significant in 'bare soil' ($p = 0.0368$) and in DM ha^{-1} ($p = 0.0023$) before and after cattle entry.

2.2.4 Nutritional Characteristics of Natural Grassland

We evaluated crude protein (CP%), acid detergent fibre (ADF%) and neutral detergent fibre (NDF%) in the natural grasslands. The ADF values obtained were used to estimate the digestibility based on the following formula: 88.9−(0.779x%ADF)

Table 21.12 Relative composition of the spontaneous natural vegetation and bare soil and dry grass before and after the introduction of animals to the SPS of *Populus deltoides* 'Australiano 106/60'

Family	Genus and species	% of coverage before entry (11/01/2008)	% of coverage after entry (05/02/2008)	Difference
Asteraceae	*Cirsium vulgare*	0,59	0,01	0,58
Asteraceae	*Conyza bonariensis*	22,76	9,78	12,98
Asteraceae	*Eupatorium hecatantum*	0,02	0,01	0,01
Asteraceae	*Gamochaeta spicata*	0,02	0,15	−0,14
Asteraceae	*Sonchus oleraceus*	0,01	0,00	0,01
Cyperaceae	*Carex riparia*	51,48	50,80	0,68
Cyperaceae	*Cyperus* spp.	3,36	1,34	2,02
Cyperaceae	*Rynchospora* sp.	0,00	0,51	−0,51
Cyperaceae	*Scirpus californicus*	1,03	0,96	0,07
Chenopodiaceae	*Chenopodium quinoa*	0,01	0,00	0,00
Poaceae	*Phalaris angusta*	2,21	0,52	1,69
Juncaceae	*Juncus* sp.	1,62	0,00	1,62
Phytolaccaceae	*Phytolacca tetrámera*	0,01	0,00	0,01
Polygonaceae	*Polygonum hidropiperoides*	11,73	10,33	1,41
	Soil without vegetation	4,17	19,69	−15,52
	Dry grass	0,97	5,88	−4,91

Table 21.13 Average wealth, Shannon Index and Jaccard Index before cattle entry, immediately after removal, 1 year later and after 18 months cattle entry into the silvopastoral trial with *Populus deltoides* 'Australiano 106/60'

Sampling data	Average wealth of sp.	Index of Shannon	Index of Jaccard
Before cattle entry (11/01/2008)	8,33	0,937	–
After cattle entry (05/02/2008)	6,55	0,741	0,333
12 months after the departure of cattle (05/01/2009)	9,16	1,29	0,250
18 months after the departure of cattle (20/07/2009)	10,17	1,10	0,227

(Ustarroz 1995). Descriptive statistics were used as measures of position and standard deviation for all variables mentioned to characterise the natural grassland.

In the four seasons evaluated, the ADF and NDF values show a progressive decrease over time (Table 21.15), while the ED and GP gradually increase, possibly

Table 21.14 Relative composition of spontaneous vegetation in plots damaged (n = 3) and undamaged (n = 3) by cattle in an SPS of *Populus deltoides* 'Australiano 106/60' in the Lower Delta of the Paraná River

Genus	Plots undamaged	Plots damaged	Difference
Carex	61,05	40,97	20,07
Conyza	16,16	30,01	−13,86
Polygonum	8,74	15,02	−6,28
Eupatorium	0,02	0,01	0,01
Gamochaeta	0,02	0,02	0,00
Cyperus	3,10	3,65	−0,56
Scirpus	0,86	1,22	−0,36
Chenopodium	0,01	0,01	0,00
Juncus	3,09	0,02	3,07
Cirsium	0,87	0,28	0,59
Phalaris	3,10	1,24	1,86
Sonchus	0,01	0,00	0,01
Sagittaria	0,00	0,01	−0,01
Phytolacca	0,01	0,00	0,01
Soil without vegetation	1,85	6,73	−4,88
Dry grass	1,12	0,81	0,31

Table 21.15 DM, GP, ADF, NDF and ED values in the natural grassland growing in an SPS of *Populus deltoides* 'Australiano 106/60' in the Lower Delta of the Paraná River

Date	DM (%)	ADF (%)	ED (%)	NDF (%)	GP (%)
11/01/2008	51,2	40,65	57,23	68,52	6
05/02/2008	52,4	41,89	56,27	67,25	6,08
05/01/2009	51,6	39,45	58,17	66,78	7,76
20/07/2009	39,8	33,95	62,45	62,01	11,57
Average	47	38,98	58,53	66,14	7,85

due to a greater presence of tender grasses and other species as shown by the average wealth and Shannon Indexes (Table 21.13). The analysis of the nutritional value of poplar leaves (Table 21.10) shows higher nutritional values than that of the grassland analysed (Fig. 21.15).

In the natural grassland of this poplar SPS, the highest ADF values were found in the summer and autumn months, respectively, and the lowest values were found in spring and winter. The highest NDF values were found in the autumn, summer and spring months, with the lowest being found in winter. The highest ED values were found during the winter and spring months and the lowest values during the autumn and summer months; meanwhile, the highest GP values were found during the winter and autumn months and the lowest values during the spring and summer months.

Although all the species present in the plots prior to cattle entry in the SPS were consumed to a greater or lesser degree, *Phalaris angusta* and *Carex riparia* were the most heavily consumed (Table 21.16).

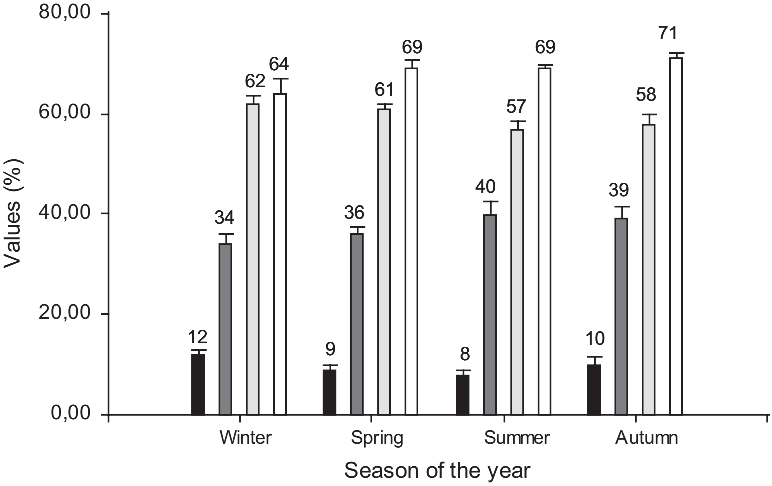

Fig. 21.15 Average values of GP (black bars), ADF (dark grey), ED (light grey) and NDF (white bars) in the natural grassland growing in an SPS of *Populus deltoides* 'Australiano 106/60' in the Lower Delta of the Paraná River, in the four seasons of the year

Table 21.16 Degree of grazing cattle

Genus and species	Degree of grazing cattle
Cirsium vulgare	2
Conyza bonariensis	1
Eupatorium hecatantum	1
Gamochaeta spicata	1
Sonchus oleraceus L.	3
Carex riparia	4
Cyperus spp.	2
Rynchospora sp.	1
Scirpus californicus	2
Chenopodium quinoa	2
Phalaris angusta	4
Juncus sp.	2
Phytolacca tetrámera	1
Polygonum hidropiperoides	1

2.2.5 Determination of Species of Forage Interest

The degree of grazing on the different species in each plot was recorded using a relative scale ranging from 0 to 4, where '0' was ungrazed, '1' was somewhat or lightly grazed, '2' was slightly or moderately grazed, '3' was always moderately and occasionally heavily grazed and '4' was always heavily grazed.

2.3 *Availability of Gross Protein in Poplar Leaves vs. Natural Grassland During the Summer Season*

The mean CP, ADF, ED and NDF values of the natural grassland vs. those of poplar leaf samples collected in October, December and March were compared using an analysis of variance (ANOVA) of two factors: one factor (type of forage) with two levels (grassland and poplar leaf) and one factor (season) with three levels (October, December and March).

The highest CP values ($p < 0.05$) were found in poplar leaves and in natural springtime natural grassland; however, significant differences were found between both types of forage (Table 21.17). The higher ED values were found in the poplar leaves in early summer and in the natural fodder grassland in spring, while lower values in poplar leaves were found in spring and late summer and in the grassland during summer (Table 21.18).

Heady and Child (1994) found that the plants preferred by livestock are the most palatable due to rich protein, sugar and fat content. Meanwhile, while the percentage of lignin and fibres increases, the percentages of simple carbohydrates and fats decrease. As a result, palatability is inversely related to lignin and fibre content. According to Choong et al. (1992), leaf hardness is directly correlated with digestibility. Herbivores reject harder leaves to avoid the relatively high cost of eating nutritionally poor food. When the vegetation surveys carried out before and after the introduction of animals to the SPS trial are compared (Table 21.14), an increase in the percentage of *Gamochaeta*, *Rynchospora*, bare soil and dry grass was detected. The drastic reduction in the percentages of *Conyza* could be due to animals trampling than consumption; *Conyza* has hairy leaves and cattle very rarely prefer this plant (Table 21.17).

Table 21.17 Comparison of the gross protein (GP) value of poplar leaves vs. that of the natural grassland in the months of October, December and March

	Season		
Kind	October	December	March
Poplar leaves	30,26a	15,79b	16,5b
Natural pastures	12,26c	7,36d	7,83d

Different letters indicate significant differences ($p <= 0.05$) between types of forage and seasons

Table 21.18 Comparison of the estimated digestibility (ED) of poplar leaves vs. that of the natural grasslands in the months of October, December and March

	Season		
Kind	October	December	March
Poplar leaves	63,73b	67,36a	62,02b
Natural pastures	65,05ab	57,52c	57,87c

Different letters indicate significant differences ($p < =0.05$) between types of forage and seasons

The mean production of DM in the natural grasslands was like that reported by Casaubon et al. 2005a; González et al. 2008 and Torrá et al. 2009, for the Delta region and in pasture of Poaceae used for raising cattle in the Pampas (González et al. 2008). Considering that forage consumption was 1999 kg DM/ha (difference between first and second sampling), that cattle generally consume between 2.5% and 3% of their live weight in DM daily (Vernet 1998) and that the grazing pressure used was 12 animals/ha, and the losses due to trampling and fouling, it may be assumed that bark damage by livestock was related to the forage biomass and/or quality after 10 days of grazing in the SPS trial, as it was mentioned by Simón et al. (1998). The plots with higher bark stripping had a greater quantity of *Carex* sp., *Juncus* sp., *Cirsium* sp. and *Phalaris angusta*, whereas those that did suffer damage had a greater quantity of species of lower forage value, *Conyza*, *Polygonum*, *Cyperus*, *Scirpus* and *Sagittaria*, and of bare soil (p = 0.0368). According to Rossi et al. (2012), *Carex riparia* has a GP of 15.6%, and *Phalaris angusta* has a GP of 16.4%.

The average ADF (38.98%) and ED (58.53%) values obtained are considered adequate for the region (González et al. 2008). González et al. (2008) and Rossi (2010) reported that the average GP of the pasture was 7.85% and that the average ED in the different samples was over 55%, the forage available in this study was considered of sufficient quality to raise cattle on the natural grassland. The quality of the forage in the natural grassland increased after the animals were removed from the SPS, possibly due to a greater presence of tender grasses and the appearance of more palatable species such as *Deyeuxia viridiflavescens*, *Leersia hexandra* (swamp ricegrass), *Lolium multiflorum* (ryegrass) and *Amorpha fruticosa* (indigo bush, false indigo) in the sampled plots.

In the region, the entry of animals into the system usually occurs in the 4th or 5th year when cuttings are used as planting material (Suárez 2006) instead of pole cuttings. This trial showed that it is possible for cattle to enter in the SPS 18 months after planting and damage to the tree shafts can be avoided by using 1 (PC1)-, 2 (PC2)- or 3 (PC3)-year-old pole cuttings with a DBH of 6 cm or greater and that damage starts to occur when there is a lack of quality forage in the system. In Chile, cattle only enter SPSs with poplars in the fourth or fifth or sixth year after planting, when the trees have reached a DBH that cannot be damaged by animals (Conaf-Infor 1997). Another example is Chilean forestry company *El Álamo*, which uses the space between the rows of poplars for agricultural production, planting a maize crop, wheat or sugar beet for the first 3 years and then using the plantations for grazing throughout the whole rotation (Sanhueza 1998b; Ulloa and Villacura 2004; Sotomayor 2009).

Another aspect worth highlighting is the diversity of species found in the natural grassland in the evaluated SPS. The disturbance caused by the use of a disc harrow on the natural grassland, followed by the grazing of the cattle and the drainage of the water on the land, facilitated the growth of valuable forage species. In this sense, water management may have contributed to turning areas that are typically marshlands into an environment enriched with forage species such as *Phalaris angusta*, *Lolium multiflorum*, *Bromus catharticus* and others (Casaubon et al. 2005a).

Although most of the spontaneous species were consumed by the cattle, some of those were more widely preferred, which enabled the creation of a degree of preference or grazing index (Table 21.15). As expected, the presence and abundance of species with low palatability, such as *Conyza bonariensis* (horseweed, fleabane), possibly contributed to an increase in damage caused by cattle to young trees. It is also possible that the DBH of these trees affected how easily they could be stripped given that only those with a DBH of less than 6 cm were affected and to a much greater extent. It is possible that the diameter acts as a mechanical barrier against livestock, given that no attempts by animals to strip the bark of individuals with a higher DBH were recorded. The damage that the cattle caused to the trees was inversely related to abundance quality species and the percentage of bare soil.

In conclusion, the 2- and 3-year-old pole cuttings with greater DBH and Ht are very good propagation materials of *Populus deltoides* 'Australiano 106/60' for SSP. To accelerate the establishment of an SPS using poplar pole cuttings, the grazing pressure or grazing time should be adjusted based on the availability and quality of forage species to ensure the sustainability of the system.

3 New Silviculture for Silvopastoral Systems with Poplars in the Delta of the Paraná

Agroforestry producers from the Lower Delta are beginning to adopt this new proposed silviculture to make more diverse use of trees and the environment. This silviculture was designed to produce a higher volume of wood per plant, good quality forage and meat from SPS. This demands organisation of the plantation area, identifying the most suitable site for the clones to be cultivated.

In the most suitable planting sites for poplars, an interesting alternative is to use 1 or 2-year-old unrooted pole cuttings with a height of 3.5–8.0 m. The nurseries providing them require planting spacing greater than the ones traditionally used in the region, excellent site quality and intensive environment management to achieve propagation materials with a sinuosity index close to 1 and a good height-to-diameter ratio. However, no data exists on the management of nurseries providing material adapted to this new silviculture for silvopastoral use. At present, the soil is prepared by crushing the spontaneous vegetation growing on the site, marking the locations of the holes and then digging the holes with a spade or a post hole digger. Plantation plots are predominantly square-shaped (5 m × 5 m and 6 m × 6 m). The pole cuttings are planted at a depth of 0.80 or 1 m, and the holes are filled with topsoil, which is rich in organic matter.

SPSs can be implemented, introducing calves of weaning age to the plantation early on. The management of the water in the stand and the lower density of trees optimise the development of trees and grass, also offering greater well-being to the livestock. In these systems, the low volume of flammable material in the understorey minimises wild fires, which are typical of the Delta. This new silviculture requires the greatest possible variety of clones to provide higher volume of wood quality for multiple uses. In this study, (1) the increase of individual growth per plant with good homogeneity of the stand, (2) an increase of percentage of cylindrical

Fig. 21.16 Silvopastoral system with 6-year-old *Populus deltoides* 'Australiano 129/60' planted from 2-year-old (PC2) unrooted pole cuttings in the Lower Delta of the Paraná River

shafts, (3) a longer planting period (May–August), (4) better plants rooting with access to the water table, (5) greater amount of forage for livestock due to an efficient management of the groundwater within the system and (6) greater planting spacing used and to pruning plants generally to heights of 7 m or greater have been demonstrated. In addition, this new silviculture achieves improved plant health by using lower plant densities, reduced plant loss due to late frost, less damage by leafcutter ants, a lower percentage of reaction wood, less wood stained by stagnant water, fewer dead plants, less competition with weeds and reduced risk of forest fires because the forage is always green and available to the livestock. In very dry summers, the good condition of the drainage networks together with the pumping and floodgate system facilitates the inflow of irrigation water into the stands; meanwhile, during periods of heavy rain, these surpluses are easily removed. These SPSs can be used to produce high-quality wood and beef with improved animal welfare (Fig. 21.16). Furthermore, the availability of water and forage encourages the presence of endangered species on the site (marsh deer, capybaras, otters and birds) (Fracassi, Personal Communication).

The findings of this study enable us to conclude that (1) it is possible to accelerate the entry of livestock into the SPS with poplars using 1-, 2- or 3-year-old pole cuttings with a DBH of 6 cm or more as propagation material, (2) sufficient supply of forage can avoid or minimise damage caused by livestock such as by bark stripping and (3) the disturbance to the environment caused by water management, the soil preparation and the grazing of animals all favour the appearance of species of spontaneous vegetation with greater forage value. Consequently, it is possible to produce quality wood for multiple uses, forage and meat in SPSs in the Lower Delta of the Paraná River (Casaubon 2013).

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Chapter 22
Cut-and-carry for Sustaining Productivity and Carbon Sequestration in Agroforestry Systems: Coffee-*Leucaena* Example

A. H. Youkhana and T. W. Idol

Abstract There is an urgent need to sustainably intensify agricultural production to address increasing human populations and respond to the challenges of climate change. One option for achieving this is the adoption of agroforestry systems. Agroforestry is 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. Cut-and-carry in agroforestry is a system in which fast-growing trees are harvested once or more per year to provide fodder for livestock or mulch and green manure for soil improvement. Using multipurpose and nitrogen-fixing trees for cut-and-carry systems can maintain or improve animal productivity and sustainability in terms of soil health and fertility. Important management factors for a cut-and-carry agroforestry system include cutting (pollarding) height, frequency, dry season management, and replacement of nutrients lost from removal of harvested material. These factors are influenced by tree species (growth and nutrient concentrations), planting density, seasonal rainfall and temperature, and soil characteristics.

In Hawaii, a novel *Leucaena* hybrid was used to develop and evaluate a cut-and-carry system for soil improvement of shade and open-grown coffee. Pruning every 6–12 months added approximately 25 Mg ha^{-1} of mulch to the soil every year, including over 150 kg ha^{-1} of nitrogen. Decay of this mulch results in a release of nitrogen beginning in the first 3 months and continuing for at least 1 year. For open-grown coffee, two years of mulch addition resulted in significant increases in surface (0–20 cm) soil carbon and nitrogen (10 and 1.42 Mg ha^{-1}, respectively). The difference in soil carbon between the mulch and no-mulch treatments was also significant (9.70 Mg ha^{-1}). Growth and yields of coffee under mulch was significantly greater than no-mulch plots fertilized with equivalent amounts of inorganic N.

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This clearly demonstrates the benefits of cut-and-carry for improving soil quality and support for organic farming practices. Projection of long-term effects of cut-and-carry systems on soil quality and crop and tree productivity should be possible with adaptation of existing models.

Keywords Agroforestry · Carbon sequestration · Century model · Climate change · Cut-and-carry · N-fixing trees · Productivity · Sustainable agriculture · Zero-grazing system

1 Introduction

Increased human populations have put a strain on limited land and other resources to produce food, fuel, and fiber in a sustainable manner (Palmer 1998). There is also increasing demand for meat products and hence the grains and fodder needed to feed livestock (Hobbs 2007). The land available for expansion of agriculture or animal husbandry is limited and typically of lower quality than lands already in production. This means there is an urgent need for sustainable intensification of lands already in production in various regions (Kassam et al. 2009; Jat et al. 2014, 2016), in particular sub-Saharan Africa and the Middle East (Sood and Mitchell 2011).

One option for achieving this is through adoption of agroforestry, which is 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 (Nair et al. 2009; Ofori et al. 2014; Wilson and Lovell 2016). In agroforestry, the biological and physical interactions among the components are manipulated to enhance the agricultural production and sustainability of the land base over time. They are structurally and functionally integrated as a management unit, although the emphasis of production can and usually does shift over time as trees grow and crops mature. Potential benefits from properly designed and managed agroforestry systems include (i) increased combined yield of all crops over time, i.e., higher land equivalency ratio, (ii) improved economic gain and efficiency, (iii) improved soil and water quality, (iv) increased biodiversity of production systems, and (v) greater net sequestration of atmospheric carbon (Nair 1993; Young 1997; Albrecht and Kandji 2003; Sharrow and Ismail 2004; Kirby and Potvin 2007; Nair et al. 2009; Upson et al. 2016). These benefits generally improve the production system's resiliency and adaptability in the face of a changing climate and weather patterns (Albrecht and Kandji 2003; Verchot et al. 2007; Nguyen et al. 2013; Mbow et al. 2014; Wilson and Lovell 2016).

Carbon (C) sequestration bears main emphasis as a potential benefit of agroforestry (Nair et al. 2009). Increasing (woody) plant biomass through integration of trees stores more carbon directly, although the extent depends upon the management of the trees, e.g., pruning to manage shade, or provides fodder or green manure.

Increased C and nitrogen (N) inputs from tree litter and roots can increase short- and long-term soil C storage. This can be enhanced when trees are pruned and used as a source of mulch or green manure (Youkhana and Idol 2009, 2011), although this clearly reduces biomass C. Reduced soil disturbance and the presence of perennial root systems can also improve soil structure and the stability of added soil C. The average C storage by agroforestry practices has been estimated as 9, 21, 50, and 63 Mg C ha^{-1} in semiarid, subhumid, humid, and temperate regions, respectively; but this varies regionally and by system. For example, C sequestration in agroforestry systems of India varies from 19.6 to 47.4 Mg C ha^{-1}, while in China it varies from 6 to 15 Mg C ha^{-1}. For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} with a tripling of carbon stocks in a 20-year period to 70 Mg C ha^{-1} (Watson et al. 2000).

Indirectly, agroforestry has the potential to offset GHG emissions associated with forest harvesting, forest degradation, and deforestation (Pandey 2002; Kumar and Nair 2011; Yohannes 2016). Various authors have speculated on the potential of agroforestry to decrease pressure on natural forests for common and low-value wood products, such a fuelwood and animal fodder (Mbow et al. 2014). Since natural forests are the largest sinks of terrestrial biomass and soil carbon, these avoided losses of C could be greater than any direct gains in the system. However, earlier concerns about the growth of fuelwood demands on natural forests have not generally been borne out. Fuelwood often is gathered from outside forested areas (Bensel 2008), and agroforestry or small woodlots tend to be adopted in areas with distant or otherwise poor forest resources (Sood and Mitchell 2011). As well, expanded production of shade-adapted cash crops like coffee (*Coffea* spp.) and cacao (*Theobroma cacao*) into undisturbed forest can actually increase forest degradation (Idol et al. 2011). The primary benefit for C sequestration seems to be in putting trees back into agricultural or degraded landscapes, enhancing wood and other resources for farm households and local and regional markets (Bensel 2008).

2 What is Cut-and-carry System?

“Cut-and-carry” is traditionally understood as a zero-grazing livestock production system, meaning the animals are confined and forage is harvested from fields and brought to the animals for feeding. Forage can include both herbaceous and perennial woody plants, although the forage itself is normally leaves and other non-woody vegetative material. Nitrogen-fixing plants are commonly included in the forage mix, and in the tropics, these are often leguminous tree species in widespread genera, such as *Leucaena*, *Flemingia*, *Calliandra*, and *Gliricidia* (Kang'ara et al. 1998; Palmer 1998) (Table 22.1).

The cut-and-carry system is not a new concept. It has been popularized recently in many countries like the Philippines, but Asian and Pacific Island farmers have been using similar systems for hundreds of years (Tonner et al. 1995; Palmer 1998), especially where land availability is limited (Aregheore 2005). One major issue of

Table 22.1 Common and scientific names and family of some trees and shrubs used for cut-and-carry system

Common name	Scientific name	Family
Prairie acacia	*Acaciella angustissima* (Mill.) Britton and Rose	Fabaceae
Lebbek tree	*Albizia lebbeck* (L.) Benth	Fabaceae
Pinto peanut	*Arachis pintoi* Krapov. and W.C.Gregory	Fabaceae
Pigeon pea	*Cajanus cajan* (L.) Millsp.	Fabaceae
Red calliandra	*Calliandra calothyrsus* Meisn.	Fabaceae
Lehua haole	*Calliandra tetragona* (Willd.) Benth.	Fabaceae
Tagasaste	*Chamaecytisus palmensis* (Christ.) Hutch	Fabaceae
Darwin pea	*Clitoria ternatea* L.	Fabaceae
Coral tree	*Erythrina buranas* Chiov.	Fabaceae
Coral bean	*Erythrina berteroana* L.	Fabaceae
Mountain immortelle	*Erythrina poeppigiana* (Walp.) O.F. Cook.	Fabaceae
Wiliwili	*Erythrina sandwicensis* O.Deg.	Fabaceae
Apa apa	*Flemingia macrophylla* (Willd.) Merr.	Fabaceae
Madre de cacao	*Gliricidia sepium* (Jacq.) Kunth ex Walp.	Fabaceae
Ice-cream beans	*Inga edulis* Mart.	Fabaceae
Haole koa	*Leucaena leucocephala* (Lam.) de Wit.	Fabaceae
Red leucaena	*Leucaena diversifolia* (Schltdl.) Benth.	Fabaceae
Giant hybrid leucaena	*Leuceana*-KX2 hybrid	Fabaceae
Moringa	*Moringa oleifera* Lam.	Moringaceae
Mulberry	*Morus alba* L.	Moraceae
Perennial soybean	*Neonotonia wightii* (Wight and Arn.) J.A. Lackey.	Fabaceae
Mesquite	*Prosopis juliflora* (Sw.) DC.	Fabaceae
Kiawe	*Prosopis pallida* (Humb. and Bonpl. ex Willd.) Kunth.	Fabaceae
Black locust	*Robinia pseudoacacia* L.	Fabaceae
Ohai ‘ula’ula	*Sesbania grandiflora* L. Poir.	Fabaceae
Egyptian riverhemp	*Sesbania sesban* (L.) Merr.	Fabaceae
Blue wiss	*Teramnus labialis* (L. f.) Spreng.	Fabaceae
Trichanthera	*Trichanthera gigantea* Nees	Acanthaceae

the cut-and-carry system is the labor required to bring the forage to the animals. Another is the loss of nutrients from the fields in harvested plant material. If uneaten fodder and animal manures are not returned to the fields, then cut-and-carry systems can be a drain on the nutrient capital and sustainability of the system. In a protein bank of *Gliricidia sepium* in Queensland, Australia, about 740 kg ha^{-1} y^{-1} of N can be exported in tree pruning (Peoples and Herridge 1990). The cutting interval of fodder trees is usually quite short to enhance the proportion of nutrient-rich foliage and young shoots in the harvested material (Catchpoole and Blair 1990). A short cutting interval also reduces forage loss in litterfall, and consequently, nutrient recycling in the foliage litter.

The use of leguminous crops for green manures is an old agricultural practice that has utilized both herbaceous and woody species (Costa and Sangakkara 2006). In wetter sites, the green manure species can be grown as a fallow-season crop or in a multi-year cropping rotation (Thierfelder and Wall 2010) and incorporated prior to planting the next crop. In drier sites or for resource-poor farmers, woody perennial crops grown as hedgerows or field borders may be preferable, given the lower need for inputs and cultivation (Costa and Sangakkara, 2006). Off-site production of green manure crops, i.e., a cut-and-carry system, has been proposed throughout the years and evaluated for a variety of cropping systems (Ruhigwa et al. 1994; Escalada and Ratilla 1998; Vanlauwe et al. 2001). As with livestock fodder, cut-and-carry for green manure or soil improvement is challenged with potentially high transportation and labor costs but significantly reduces or eliminates the competitive interactions and space requirements of in-field production of green manures.

3 Why is Cut-and-carry Important?

Using cut-and-carry has increased recently to overcome the demand of grazing and soil improvement. However, the addition of manure, compost, or mulch (plant biomass) in a cut-and-carry system is an agroecosystem management strategy commonly used in tropical regions to help maintain soil fertility and improve nutrients (i.e., phosphorus (P)) availability for crop growth (Pretty 2008). In a cut-and-carry system, defined as the transfer of biomass from external sources to the area of crop production, mulch is strategically located on the soil surface. The mulch biomass acts as a soil protector by minimizing erosion and as a soil amendment by enhancing soil fertility and crop yield (Young 1997). Biomass for cut-and-carry systems is typically obtained from perennial trees or legumes that can acquire a large fraction of P from relatively less available forms of soil P and are capable of accumulating a greater P concentration in leaves (Buresh et al. 1997). In Ghana, Partey et al. (2011) observed that *Tithonia diversifolia* leaves had the greatest rate of decomposition and nutrient release rates when compared to four other leguminous species, *Senna spectabilis*, *Gliricidia sepium*, *Leucaena leucocephala*, and *Acacia auriculiformis*, as mulch biomass in agroforestry systems.

Soil fertility on tropical agricultural lands is in decline in many areas as a result of continuous nutrient removal through crop harvests, shorter cropping cycles and fallow periods, expansion of agriculture to marginal lands, inadequate or inappropriate use of organic or inorganic fertilizers, and lack of incentives for soil conservation practices (Hartemink 2003). Although tropical soils are highly diverse, in many areas, they are naturally susceptible to nutritional deficiencies; in Southeast Asia and South America, nutrient stress, together with chemical toxicities, affects half or more of the soils (Larson 1986). Depletion of soil fertility reduces agricultural yields and aggravates food insecurity (Sanchez 2002). Nevertheless, in public discussion on food security, the changes in the quality and fertility of soils as the primary physical resource supporting food systems often get shadowed by other issues such as land tenure or climate threats (Stocking 2003).

Nitrogen is one of the most important nutrients in sustaining agricultural production globally. While it is seldom the limiting nutrient in natural ecosystems in the humid tropics, serious N deficits may develop in agroecosystems when N is exported in considerable amounts with crop harvest (Martinelli et al. 1999; Vitousek et al. 2002; Lal 2004).

Farming practices affect the sensitivity of soils to degradation. Practices which integrate soil conservation can help counteract degradation and loss of fertility and provide alternative or complementary approaches to the use of inorganic fertilizers (Jensen and Hauggaard-Nielsen 2003). Improved fallows or intercropping with legume plants which form symbiosis with N-fixing bacteria can replenish and maintain soil fertility by contributing to the accumulation of soil organic matter and particularly N (Peoples and Herridge 1990; Giller 2001). For many legume tree species, symbiotic N-fixation accounts for 30–90% of tree total N under varying natural conditions (Giller 2001). Legume trees may contribute up to 270–550 kg N ha^{-1} year^{-1} to the N balance of agroecosystems (Jayasundara et al. 1997; Dulormne et al. 2003), and agricultural crops cultivated with N-fixing trees have been shown to benefit from the association (Chalk 1998). Nitrogen of atmospheric origin constituted from 13% to 42% of total N in coffee (*Coffea arabica*) in several coffee-legume tree associations (Snoeck et al. 2000), up to 21% in *Setaria sphacelata* grass in association with legume trees *Gliricidia sepium* and *Leucaena leucocephala* (Jayasundara et al. 1997), and from 31% to 35% of N in fodder grass *Dichanthium aristatum* intercropped with *Gliricidia sepium* (Sierra and Nygren 2006; Daudin and Sierra 2008).

4 Trees Used for Cut-and-carry System

Many tropical and subtropical tree and shrub species have been grown and managed for fodder, including cut-and-carry systems (Table 22.1). Desirable characteristics of species for this purpose include easy propagation and rapid establishment after out planting or direct seeding, competitiveness with herbaceous weeds, fast growth, high digestibility of leaves and other non-woody components, vigorous sprouting after repeated harvesting and pollarding, a tap root or deep root system, ability to remain productive during dry periods, ability to thrive on nutrient-poor soils, and N-fixation capability (Roshitko 1994). These trees are often considered multipurpose, since the same characteristics that make them amenable to fodder or green manure production also make them desirable for other purposes, such as fuelwood production, windbreaks and live fences, managed shade for shade-adapted crops, or even human consumption of leaves, seeds, or young shoots. Despite the variety and great utility of woody legumes for fodder and green manure production, only a few of the tree species have been subject to significant breeding improvement programs, e.g., *Leucaena leucocephala* subsp. *glabrata* and hybrids with other species in the genus (Brewbaker 2008, 2013).

5 Using Cut-and-carry for Basic Grazing System

In cut-and-carry grazing systems, most of the feed is obtained outside the surrounding farm land. Forages may be transported from as far as 2 to 5 km away from the animal confinement area. Adoption of cut-and-carry is often an indicator of limited agricultural land; surrounding fields are prioritized for crop production, and more distant pasture or forest land is used to gather forage for animals. A contributing factor may also be local laws or regulations that limit communal grazing of crop land, even in the fallow season (Aregheore 2005). Constraints include availability of forage, especially during the dry season, labor availability, distance of feed from the farm, means of transport, and access rights to feed on private, communal, or public land. Cut-and-carry is, thus, common in many regions, e.g., Pacific Islands, where high mountain environments limit grazing land availability and a generally wet climate allow for year-round growth of forages and N-fixing trees and shrubs. These include Fiji, Samoa, Tonga, the Cook Islands, Vanuatu, the Solomon Islands, and Papua New Guinea (Macfarlane 2000). Cut-and-carry is also common although not the dominant grazing system in parts of Southeast Asia, Sri Lanka, and in the Caribbean. In their native range of Central America, *Leucaena leucocephala* and *Gliricidia sepium* are commonly planted as field borders and live fences and harvested for animal fodder rather than directly grazed (Simons and Stewart 1994). However, cut-and-carry animal production systems may hold the most promise in South and Southeast Asia and sub-Saharan Africa, i.e., those areas most in need of sustainable intensification: First, the combination of increasing populations and limited availability of suitable agricultural land for expansion means that existing arable land needs to be prioritized for human food production. Second, many small farmers in these regions also keep livestock, often grazing in fallow agricultural fields during parts of the year. In Asia, free-grazing animal systems compete with food production and contribute significantly to the degradation of remaining forests (Palmer 1998). In monsoonal India and sub-Saharan Africa, dry season grazing of crop fields provides important fodder for livestock but depletes soils of organic cover and undermines attempts to grow green manures or most cover crops (Giller et al. 2009). Research into integrated crop-livestock systems is a priority for the United Nations Food and Agriculture Organization to address the challenges of protecting soils and agricultural productivity while meeting the demands for livestock production (FAO 2017).

A general rule in cut-and-carry is to give freshly cut forage equivalent to about 10% of an animal's body weight daily. Ideally, half of the cut forage should be given in the morning and the rest in the evening so that the animal can make more efficient use of it and reduce waste (Aregheore 2005). The quality and the year-round availability of forage resources are important because farmers look for the best forage to harvest. However, nutrient export from cut-and-carry fodder production systems is a concern for sustainability, especially if forage trees and grasses are grown in the same plot (Nygren and Cruz 1998). As the name implies, the fodder is cut and carried to animal stalls. Farmers have a long been practicing this system. Legumes such as species of *Ficus*, *Acacia*, *Leucaena*, *Gliricidia*, and *Albizia* are the most preferred fodder tree species (Mathukia et al. 2016). Cut-and-carry systems using fodder trees, especially N-fixers, can maintain or improve animal productivity and sustainability in terms of soil health and fertility (Dulormne et al. 2003).

There are important management factors that should be considered for a cut-and-carry system utilizing trees, such as cutting (pollarding) height, cutting frequency, and dry season management. These factors are influenced by species (growth), density (planting spaces), climate (rainfall, temperature), and edaphic factors. Interactions are unique for each situation, resulting in effective management prescriptions that differ at each site. For N-fixers, it is also important to understand the dynamics of N-fixation and the turnover of the fixed N for optimal development and management of these systems (Ladha et al. 1993; Jalonen et al. 2013). Pruning of tree shoots often causes dieback of fine roots and, for N-fixers, loss of N-fixing nodules and thus N-fixation capacity. Recovery of N-fixation takes time, of course, and it may depend upon follow-up management practices. For example, mulching of pruning residues in the tree rows can improve N-fixation, but reincorporating the cut shoots as green manure, as would be done with hedgerow intercropping, may suppress N-fixation for some species but not others (Kadiata et al. 1997).

6 Using Cut-and-carry System for Soil Improvement

Soil organic matter (SOM) is important to sustain soil quality, which has been recognized since ancient times. Particulate SOM, as with crop residues and other organic surface litter, insulates the soil from temperature fluctuations and protects it from raindrop impact. Humified SOM improves soil particle aggregation and thus soil structure, and it decreases soil bulk density (Youkhana and Idol (2009, 2011). These effects enhance water infiltration and reduce runoff and erosion. It also has a high water-holding capacity but also a rapid release rate, so most of the absorbed water is available for plant uptake. And all forms of SOM are key components of nutrient recycling, which is particularly important in low input cropping systems. Resource-poor farmers usually cannot fully replace the soil nutrients removed in crop harvests because of insufficient availability or high cost of organic or inorganic fertilizers (Phiri et al. 2001). Crop residues and weed biomass can help maintain SOM and recycle nutrients; however, they are usually not sufficient to sustain SOM, nutrient supply, and thus crop productivity. Furthermore, most nutrients in crop residues are not readily available and may even induce net nutrient immobilization in the short-term (Palm et al. 2001; Vanlauwe and Giller 2006).

Trees have been used in agroforestry systems to replace and recycle soil nutrients and restore or enhance SOM through natural litter production and addition of pruning residues (Palm 1995; Cobo et al. 2002). Tree roots can reach deeper in the soil, extracting nutrients and then recycling them at or near the surface soil. Decomposing, nitrogen-rich leaves and twigs are usually thought to be the main mechanism of nutrient cycling from N-fixing trees (Beer et al. 1998; Giller 2001). In many agroforestry systems, the trees are frequently pruned to provide green manure to the crops. Pruning also temporarily reduces competition with crops for light, water, and nutrients, although it generally increases the competition for soil N; the trees absorb more N from the soil during regrowth because turnover of the N-fixing nodules impedes N-fixation (Nygren 1995; Nygren and Ramirez 1995). The quality of aboveground plant parts as N sources have been studied in numerous studies (Mafongoya et al. 1998, Palm et al. 2001, Youkhana and Idol 2009). It is important to understand the effects of different pruning regimes on the dynamics of N-fixing nodules in the cut-and-carry forage production. *Gliricidia sepium* is perhaps the most widely cultivated multipurpose tree in the tropics after *Leucaena leucocephala*. It is an important component of cut-and-carry forage production systems in Southeast Asia, Sri Lanka, and in the Caribbean, while living fence systems are preferred in its native range in Central America (Simons and Stewart 1994). Litter quality of some trees may be no better than crop residues, though; so mixtures of vegetative inputs with animal manures or even inorganic fertilizers can result in better outcomes for plant nutrition, even when using litter from N-fixing species (Mittal et al. 1992; Vanlauwe et al. 2001). Natural litterfall from *Erythrina poeppigiana* trees used as shade for coffee in Costa Rica added 200 kg N ha^{-1} y^{-1} (Schroth et al. 2001). Regardless, the addition of tree litter or pruning residues can be a valuable addition to crop residues to boost the quantity of organic matter and nutrients recycled in cropping systems.

Transformation of plant residues into humified SOM is necessary to realize many of the touted benefits for soil properties and processes. Slower decomposition does not necessarily translate into a greater stabilization of residues as humified SOM. Residues confined mainly to the surface will be largely mineralized as CO_2 due to the lack of protection from microbial decay by soil particles and aggregates. Incorporation of surface residues into the soil does speed decomposition, but it also increases physical and geochemical protection of the remaining fractions of the residues. And since humified SOM is largely made up of microbial byproducts of decay, increasing the food source and subsequent biomass of microbial decomposers should also increase this pool of humified SOM. Furthermore, there is evidence that the increase in organic N compounds in soils from N-fixing plants may increase biochemical protection of existing pools of SOM against decay (Resh et al. 2002; Binkley 2005).

Many studies of agroforestry systems with trees grown alongside crops have shown increased SOM over time (Altieri et al. 2015). However, not many have investigated cut-and-carry systems for their effects. This is important, since the effects of trees on SOM are more complex than just addition of surface litter or pruning residues, e.g., the growth, activity, and turnover of fine and coarse roots from the trees. Various reports have shown that trees and shrubs, due to their deeper roots systems, are more effective in taking up and recycling plant materials than herbaceous or grass fallows (Lundgren 1978; Jordan 1985). Milsum and Bunting (1928) were among the earliest researchers to suggest that herbaceous legumes were not suitable sources of green manure in the tropics. They believed that shrub legumes, including some perennials such as *Crotalaria* sp. and *Cajanus cajan*, were more suitable. They even suggested a cut-and-carry method in which leaves cut from special green manure source plots would be used to manure other plots on which crops would be grown. In one study, Kimemia et al. (2001) showed that the application of green manure derived from *Leucaena leucocephala*, *Sesbania sesban*, *Calliandra calothyrsus*, *Medicago sativa*, *Desmodium intortum*, and *Cajanus cajan* to coffee plants in a cut-and-carry system resulted in an increase of 19 and 42% in soil organic carbon and exchangeable acidity, respectively.

In many agroforestry systems, trees are pruned or pollarded periodically to manage shade levels and the extent of the canopy. Pruning residues, especially leaves, twigs, and small branches, may be used as soil cover or green manure if not fed to animals. Direct placement of branches and leaves is generally less uniform and effective than chipping and mulching of the tree pruning residues to capture the benefits of organic matter, nutrient additions, and continuous soil cover (Snoeck 1961; Kimemia et al. 2001). Mulching, while requiring more labor and often machinery to uniformly chip the pruning residues, can lower soil bulk density in comparison with areas where no mulch has been applied (Youkhana and Idol 2009). Kimemia et al. (2001) found bulk density reductions within a range of 8–25% after 3 years of mulch applications from seven agroforestry species in Kenyan coffee plantations. Continuous organic soil cover (mulch) can also better suppress weed growth, reduce water runoff and erosion, insulate the soil from extremes of heat, reduce surface evaporation, and stimulate soil biological activity (Hobbs 2007). Most tree mulch makes a poor nutrient source, though, since wood generally has a low nutrient concentration. That may be less the case with mulch from N-fixing trees, since they generally have a higher N concentration than other tree species.

Considerations for residue application include not only the quantity and quality of the residues but also the timing. The quality of tree residue materials influences the decomposition rate; plant materials with high N and low lignin and polyphenol contents decompose more readily and release nutrients faster (Jamaludheen and Kumar 1999). This relationship makes it possible to manage the rate of nutrient release. For example, a 44% higher maize yield was obtained when high-quality *Erythrina poeppigiana* mulches were used as a N source for short-term crops like maize and beans using 20 Mg fresh weight ha^{-1} applied twice a year, compared to the control with no residue addition (Kass et al. 1993).

To achieve synchrony between N supply from prunings and N demand by the crop, relatively large amounts of N should be released into the soil before peak N demand by the crop. This could be achieved for maize with N-fixing trees by incorporating adequate quantities of their high-quality prunings (Mafongoya and Nair 1996; Kamara et al. 2000). Alternatively, high-quality plant residues can be added to inorganic N fertilizers as a supplement or even to boost the efficiency of total N uptake (Mittal et al. 1992; Vanlauwe et al. 2001).

Various researchers have explored the use of N-fixing trees for soil improvement in a cut-and-carry system. In some cases, it has been investigated as an alternative to alley cropping, since it reduces competition with the crop plants. Major trade-offs are the extra requirement for available land that is suitable to grow trees and the extra labor associated with transportation.

Dedicating woodlots or other small tree plantations of N-fixing species within a cut-and-carry system may be an option for farmers where incorporating trees in crop fields is not feasible or insufficient to provide adequate soil cover. Fuelwood plantings can be quite diverse in size and purpose, including intercropped agroforestry systems, and may utilize multipurpose trees that could also serve as mulch or green manure in cut-and-carry systems, as in Central America (Westphal 2008). In Central America, fuelwood is normally harvested from N-fixing trees like *Inga* and *Gliricidia* spp. (Westphal 2008), which are also commonly used for cut-and-carry fodder, mulch, or green manure. While many small fuelwood plantings are dedicated to household use, where there is increasing demand for wood fuel and charcoal, commercial plantings provide significant opportunities to reforest degraded lands and generate income for producers. Thus, there are likely opportunities to develop and capitalize on cut-and-carry fodder and soil improvement systems within existing cut-and-carry fuelwood production systems.

7 Cut-and-carry System for Full-sun Coffee: A Case Study

While coffee is a shade-adapted plant, it is increasingly grown in intensive, full-sun plantations. One option for full-sun operations is the use of a “cut-and-carry” system in which a stand of N-fixing trees is grown outside the coffee field and utilized as a source of mulch to capture the benefits of organic matter, nutrient additions, and continuous soil cover (Kimemia et al. 2001; Youkhana and Idol 2016). Although this requires additional growing space, trees can be grown on areas less suitable for coffee or at least mechanized operations, such as degraded soils, sloping areas, or uneven terrain. Alternatively, trees can be planted at field borders, as with wind breaks or live fences. Chipping of pruning residues, which include a mixture of leaves, seed pods, branches, and orthotropic shoots from the main stem (Fig. 22.1), also ensures a uniform material that is easier to spread in the field and should decompose faster due to increased surface area, soil contact, and the mixture of residues with higher and lower nutrient concentration and ratios of C:N and lignin:N. Understanding litter quality, such as C:N and lignin:N ratios, can improve

Fig. 22.1 Leucaena-KX2 as a source of mulch for an experimental cut-and-carry system in Hawaii

Table 22.2 Mass loss from *Luecaena*-KX2 mulch biochemical fractions as a percentage of the initial mass

Months	Carbohydrate	Hemicellulose	Cellulose	Lignin	Ash
0	33	29	21	13	4
3	27.7	20.1	13.8	8.3	2.7
6	19.5	14.0	9.5	5.5	2.0
9	16.3	11.6	7.7	4.3	1.7
12	13.1	9.5	6.2	3.3	1.5

understanding and prediction of decay rates, N mineralization, and effects on SOM using standard models, such as Century model (Parton and Rasmussen 1994). However, few studies have tracked changes in these litter quality parameters over time (Berg and Ekbohm 1991).

Because *Leucaena* spp. and hybrids are excellent N-fixers (Brewbaker 2008, 2013), mulching of the pruning residues acts like a slow-release fertilizer to the soil. This may also help to build up the soil organic matter level (Youkhana and Idol 2011). Results from several studies in Hawaii with *Leucaena* hybrid KX2 used as in-field shade for arabica coffee clearly demonstrated increased total soil N and C and lower soil bulk density (Youkhana and Idol 2009, 2011). A pollarding frequency of 6–12 months added approx. 25 Mg ha^{-1} of mulch to the soil every year, including over 150 kg ha^{-1} of N. Decay of this mulch resulted in a release of N beginning in the first 3 months and continuing for at least 1 year. After only 2 years, soil C in the top 20 cm also increased significantly by over 10 Mg ha^{-1}. This included both labile and more stable soil organic matter fractions (Youkhana and Idol 2011). The cycling of organic N and other improvements in soil quality from pollarding and mulching can support organic coffee production (Youkhana and Idol 2010).

Despite these soil benefits, maximum coffee yield was still achieved under full-sun with only inorganic N applied (Youkhana and Idol 2010). Thus, a companion study was carried out to test whether a cut-and-carry mulching system could achieve benefits to both soil quality and coffee yields under full sun. In this study, coffee plants were established in a field adjacent to a seed orchard of *Leucaena*-KX2 trees planted on a 2 × 2-m spacing. The trees were pollarded and mulched every 6 months, and mulch was added to coffee plants on an area-equivalent basis, namely, 2 × 6-m plots of trees or coffee plants. Plots of no-mulch coffee were fertilized with equivalent amounts of inorganic N, with other nutrients added, as needed.

Results from this study (Youkhana and Idol 2016) were similar. Approx. 64% of *Leucaena*-KX2 mulch added to full-sun coffee plots using cut-and-carry was decomposed after 1 year, and the mass loss occurred in all the major biochemical components in the mulch added over time, including lignin and cellulose (Table 22.2). The C:N ratio of mulch declined from 50:1 to 40:1, and the lignin:N ratio declined from 13:1 to 10:1.

After two years of mulch addition, the increase in soil C was 10 Mg ha^{-1}, approximately 20% of the C added in mulch. The difference in soil C between the mulch and no-mulch treatments was also large (9.70 Mg ha^{-1}). In the shade coffee system,

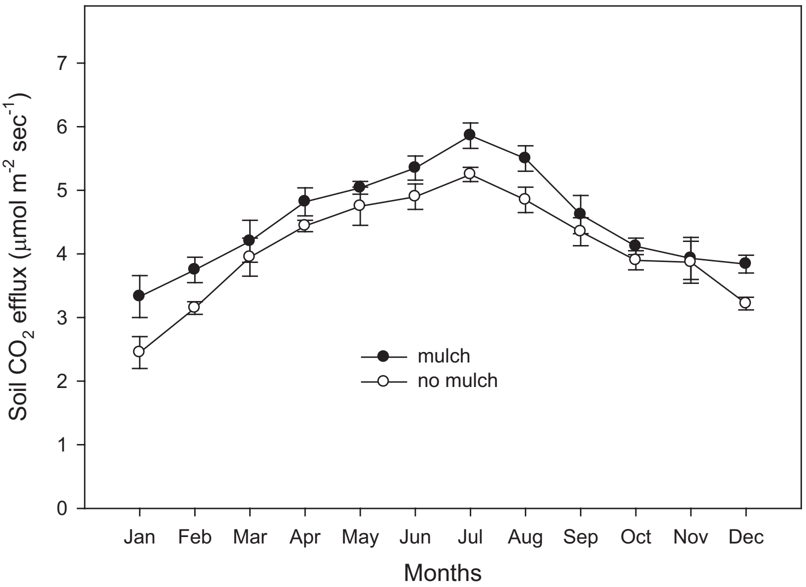

Fig. 22.2 Monthly average of soil CO_2 efflux (μ mol m^{-2} s^{-1}) from mulch and no mulch experimental full-sun coffee plots in Hawaii using cut-and-carry system

the increased soil C after three years of mulch addition was 38% of the C added as mulch. Longer-term studies suggest a 10–15% annual rate of sequestration can be maintained for at least 10–20 years (Fassbender 1998). An average 10% sequestration rate over 10 years would result in a total of 25 Mg ha^{-1} of additional soil C in the study area. Accounting for this capture is important not only from the perspective of understanding SOM changes but also because pollarding and mulching removes live biomass C, much of which is in long-lived woody tissues.

Since most mulch C did not end up as SOM, much of the rest likely was lost in respiration during mulch decomposition. The deposition of abundant and easily decomposable, nitrogen-rich litter is known to result in increased soil atmospheric CO_2 concentrations (McLain and Ahmann 2008) and soil respiration, e.g., under *Prosopis* spp. (Potts et al. 2008). In Youkhana and Idol (2016), CO_2 efflux increased gradually over time (Fig. 22.2), reflecting the effect of mulch decay on total soil organic matter and cycling activity rather than direct mulch C mineralization.

Leucaena has been used as a N source for coffee in other parts of the world for many decades (Snoeck 1961), but typically only leaves and small branches have been used as green manure. Youkhana and Idol (2009, 2016) demonstrated clearly that mulched tree pruning residues can provide an early and sustained source of mineral N to crop plants. This pattern has been documented for other N-fixing trees in agroforestry systems (Munroe and Isaac 2014). The loss of mass from all biochemical fractions of mulch may help explain why N was mineralized relatively early and continued throughout the year. The mixture of higher- and lower-quality

Fig. 22.3 Full-sun coffee system (Hawaii): tree with mulch (left) and no-mulch (right)

components in the mulch and the fact that fresh rather than dried or senesced plant material was added as mulch likely account for our more immediate and sustained loss of N. This should sustain the N needs of crop plants like coffee until fresh mulch additions can replace the N and organic matter lost due to mulch decay.

Using *Leucaena*-KX2 as mulch for open-grown coffee resulted in significantly greater growth and productivity of various components, including stem diameter and height and leaf chlorophyll content, and various components of coffee yield, including the number of fruiting laterals/stem, fruiting nodes/lateral, and fruits/node, the weight of 100-bean samples (Youkhana and Idol 2016). Coffee plants were visibly larger, healthier, and with lower weed pressure in mulch plots. (Fig. 22.3).

8 Discussion and Future Expectations

Because tree-based cut-and-carry systems can provide high-quality animal forage or mulch and green manure for soil improvement, they can offset competing demands of organic amendments for organic fertilizers, animal fodder, fuel, or sales for income, which often restrict fertilizer use (LEAD 1999). The major challenges are, as with any cut-and-carry system, namely, labor and transportation costs. The animals may be a great distance from the fodder bank or just across a protective fence. Special harvesting equipment is available for harvesting green manure, but all that is necessary for tree-based systems is a sharp machete. A cut-and-carry system decreases fodder waste from animal damage and the necessity to monitor animals. However, labor inputs are still greater than with direct grazing systems.

Compared to herbaceous fodder or green manure/cover crops, cut-and-carry may be more desirable for trees, since competitive interactions and space requirements are greater when grown in crop fields. Compromise systems, such as growing trees along field borders, can reduce transportation distance while creating benefits from the additional products and services from agroforestry, such as wind protection, fuelwood, habitat or other resources for pollinators and pest predators, and soil and water conservation. Cut-and-carry systems using multipurpose fodder trees (N-fixers) have demonstrated the ability to sustain, maintain, and improve animal productivity and soil quality. The dynamics of N-fixation and the turnover in these systems are important for optimal development and management (Jalonen et al. 2013).

Studies using a N-fixer tree like *Leucaena*-KX2 as a source of cut-and-carry mulch and green manure for a full-sun coffee system have demonstrated significant soil quality improvement and greater crop growth and yield. The productivity of trees on an equivalent-area basis was sufficient to provide year-round soil cover and immediate and long-term N supply sufficient to meet the needs of the crop. The trade-offs relative to shade-grown coffee is greater need for productive land and smaller average bean size, which is perceived as being of lower quality and thus fetches a lower market price in the Hawaii coffee market (Youkhana and Idol, 2010).

9 Cut-and-carry Model of Full-sun Coffee System

Although a few models have been developed and applied in agroforestry and organic farming (Oelbermann and Voroney 2011; Luedeling et al. 2016), there is no specific model for a cut-and-carry system to add mulch or green manure for soil improvement and crop production. Existing SOM models like CENTURY or DNDC do offer scope for adaptation to this type of system to explore the potential long-term effects on SOM cycling and crop productivity component based on N (Cole et al. 1987; Parton et al. 1987; Li et al. 2003; Zhang and Niu 2016). CENTURY was especially developed to deal with a wide range of cropping system rotations and tillage practices for system analysis of the effects of management and global change on productivity and sustainability of agroecosystems. The DNDC model couples the basic soil-plant-climate interactions of CENTURY to crop-specific production models. CENTURY simulates both above- and belowground biomass production of crops, grasslands, forests, or savannas (Parton et al. 1988). A soil organic matter submodel predicts changes in levels of SOC based on microbial decomposition and of plant residues; the resulting microbial byproducts are the substrate for humus formation (Parton et al. 1988).

It should be possible to adapt the CENTURY model to cut-and-carry systems for a variety of cropping systems. A conceptual model for cut-and-carry as applied to full-sun coffee is shown in Fig. 22.4. The model incorporates the specific inputs and

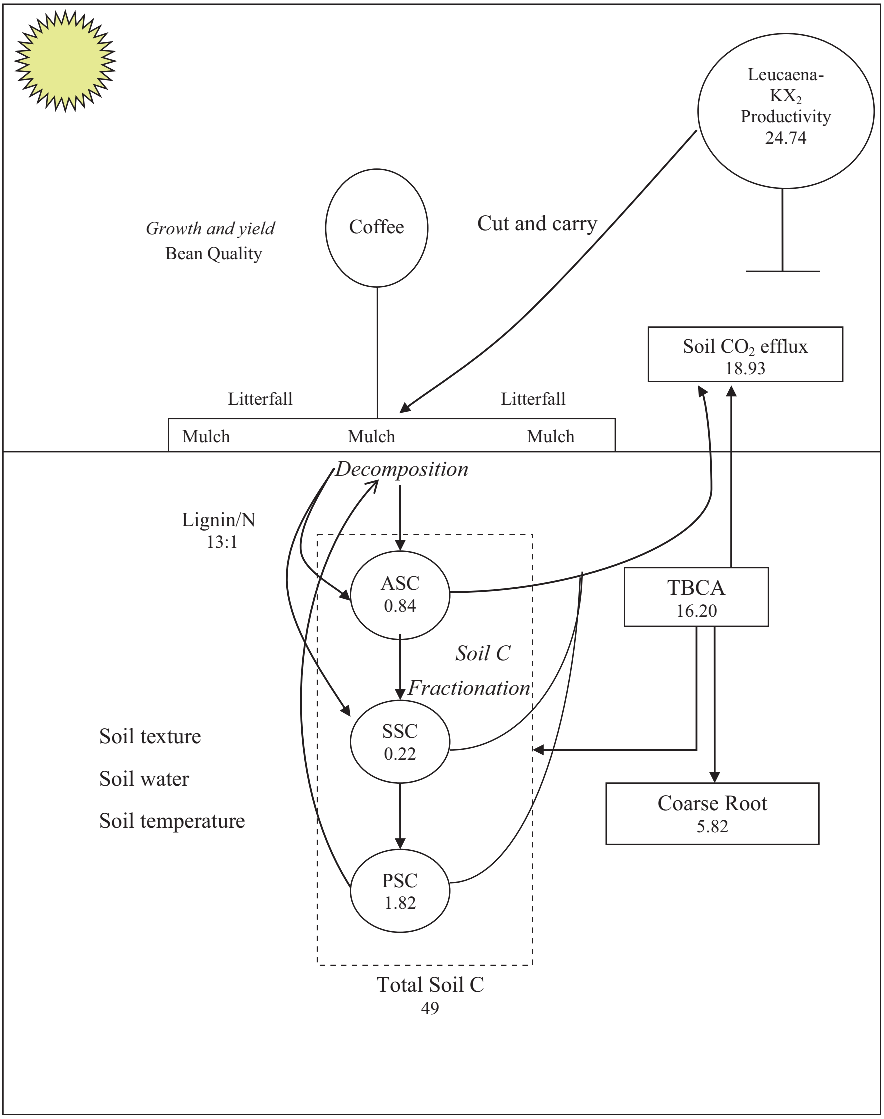

Fig. 22.4 Cut-and-carry conceptual model for full-sun-grown coffee

fluxes in a cut-and-carry system. As with CENTURY, it uses a C balance approach to estimate total belowground allocation (TBCA) over time with mulch addition. The theoretical soil C pools in CENTURY can be linked to measured soil organic matter fractions (Six et al. 2002). The values in the model are based on actual measurements; thus, they represent the starting point for adaptation and validation of CENTURY or a related model like DNDC for a cut-and-carry system. The most significant adaptation needs are for the tree production module, given the regular harvesting and resprouting of the tree component, and the soil C module under the trees, since harvesting removes nutrients from the tree component, increasing the demand on soil nutrient supplies during regrowth but also reducing litter inputs from harvested biomass. This should be possible, since harvesting and biomass removal from the trees is analogous to yield harvests from crop plants.

10 Conclusion

Cut-and-carry in agroforestry is a system in which fast-growing (N-fixers) trees are harvested once or more per year to provide fodder or mulch and green manure for soil improvement. As with livestock fodder, cut and carry for green manure or soil improvement is challanged with high transportation and labor costs but significantly reduces the competitive interactions and space requirements of in field production of green manures. The important management factors related to cut-and-carry agroforestry system include cutting height and frequency, dry season management, and replacement of nutrients lost from removal of harvested material. Long-term projection impact of cut-and-carry systems on crop and tree productivity and soil quality should be possible with adaptation of existing models like CENTURY or DNDC.

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Chapter 23
Multistrata Systems: Potentials and Challenges of Cocoa-based Agroforests in the Humid Tropics

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Abstract Multistrata agroforests comprise a wide range of agroforestry practices that includes assemblage of woody and nonwoody plant components, with the wide range of practices on the continuum from using shade trees in perennial plantation to very diversified agroforests that mimic the original forest-like structure. In the humid tropical lowlands, such systems often consist of cocoa (*Theobroma cacao*) grown under the shade of trees. In this review, we explore the reliability of research on and the feasibility of achieving the environmental and economic benefits of cocoa agroforests, highlighting future opportunities and challenges of cocoa growing. Unsustainable intensification in a form of monocultures with high agricultural inputs reduces ecological resilience of a land-use system, whereas paradoxically, environmental and climate changes require more than ever a higher capacity of land-use systems to cope with increasing global environmental pressure. Over the past decade, a number of new studies focusing on cocoa agroforests have been published. We review current cultivation of cocoa in the world and outline the establishment and management of cocoa agroforests. Further on, we explored the idea that cocoa agro-

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forests could be a solution to prevent phenomenon of boom-and-bust cycle of cocoa cultivation and highlighted the possibilities for improvement of cocoa cultivation using its vast genetic base. Then the benefits of cocoa agroforests for (agro)biodiversity and soil conservation are summarized and economic perspectives of multistrata systems assessed. In final discussion, we performed a SWOT analysis, highlighting future opportunities and challenges and proposing recommendation to improve the extension, adoption and sustainability of cocoa agroforests.

Keywords Agrobiodiversity · Cocoa farming · Genetic diversity · Soil management · SWOT analysis · *Theobroma cacao*

1 Introduction

Agroforestry as a land-use practice increases ecological integrity and provides sustainable benefits for smallholders while enhancing their resilience in the face of social and ecological change (Mathez-Stiefel et al. 2016). Multistrata agroforests comprise a wide range of agroforestry practices that includes assemblage of woody and nonwoody plant components, with the wide range of practices from simple use of shade trees in perennial plantations on one end to very diversified agroforests that and in fact mimic the original forest-like structure on the other. It is usually composed of several plant layers or strata: a herbaceous layer, a low- and high-shrub layer, and/or medium- and tall-tree layer, all of them or their combinations. Multistrata agroforests are usually very complex and hard to define, as the name covers the continuum from highly stratified through extra-actively used natural forests and traditional homegardens, over mainly tree-based multistrata agroforests until rather simplified agroforests, focusing on commercial growing of specific

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plantation crops. The latter simple multistrata system is characterized by a cultivation of one main cash crop grown in association with shade trees. Most of these agroforests with a cultivated tree cash crop component occur in the tropics where they provide a range of environmental services. In the humid tropical lowlands, such perennial crop-based agroforestry systems often consist of cocoa (*Theobroma cacao*) or robusta coffee (*Coffea canephora*), grown under the shade of trees. In the tropical highlands of Africa or South and Central America, common agroforestry systems consisting of shaded arabica coffee (*C. arabica*) or tea (*Camellia sinensis*)-based systems are prevalent (Atangana et al. 2014). Other examples of important perennial crops that can be grown in multistrata agroforests are coconut (*Cocos nucifera*), oil palm (*Elaeis guineensis*) and rubber tree (*Hevea brasiliensis*), the latter two mainly combined with other trees or food crops, usually only for a short period after plantation establishment.

The most common agroforestry crops, coffee and cocoa, cover more than 20 million ha in the tropics (in 2013, FAOSTAT 2016), account for the largest legal international commodity trade volume besides petroleum (Donald 2004) and can be grown in conditions that through vegetation structure mimic natural forests more closely than other cropping systems (Schroth and Harvey 2007). However, they can be also grown in very simplified monocropping systems. This industrial, large-scale, monoculture farming of plantation crops is usually more productive than agroforestry systems; long-term sustainability is threatened by extremely high cultural, social and environmental costs (Tilman et al. 2002). This agricultural intensification reduces ecological resilience of a land-use system, whereas paradoxically, global environmental and climate changes require more than ever a higher capacity of land-use systems to cope with increasing environmental pressure (Tscharntke et al. 2011).

The global challenge facing the cocoa sector today is how to increase production to meet the growing demand by chocolate-producing companies without expanding the area under cultivation (Vaast and Somarriba 2014). Diverse cocoa agroforests may sustain livelihoods of smallholders as well as provide ecological benefits such as biodiversity conservation within human-dominated tropical landscapes (McNeely and Scherr 2003; Franzen and Mulder 2007; Clough et al. 2009). Commercial multistrata agroforests can probably bridge economic profitability and sociocultural value with conservation of wild and cultivated biodiversity (Steffan-Dewenter et al. 2007). On the other hand, the establishment of cocoa plantations is often blamed for deforestation (Ruf and Schroth 2004; Clough et al. 2009, 2011), caused by the common feature of the boom-and-bust cycle of cocoa cultivation.

In this review, we explore the reliability of research on and the feasibility of achieving the environmental and economic benefits of cocoa agroforests. The growing demand for cocoa (ICCO 2012) indicates that contemporary cocoa cultivation needs to be sustainably intensified or expansion into the new pristine land would be hardly avoidable. Over the past decade, lots of new studies focusing on cocoa agroforestry systems have been published. In the first part of the chapter, we would like to review current cultivation of cocoa in the world and outline the establishment and management of cocoa agroforests. Our next aim was to explore the idea that cocoa agroforests and its management practices could be a viable solution to prevent phenomenon of boom-and-bust cycle of cocoa cultivation. We would like to highlight the possibilities for improvement of cocoa cultivation using its vast genetic base through breeding and genetic improvements. Further on, the benefits of cocoa agroforests for agrobiodiversity, biodiversity conservation in general, soil and water conservation are reviewed. Finally, economic perspectives of multistrata systems are given. In the final discussion, we perform a SWOT analysis, highlighting future opportunities and challenges and proposing recommendation to improve the extension, adoption and sustainability of cocoa agroforestry.

2 Current Extension in the Tropics

Cocoa tree is explicitly an understorey forest species, which evolved in the Upper Amazon (Motamayor et al. 2008) but is currently grown in about 60 countries mainly on small-scale family farms (Lass 2004; FAOSTAT 2016). Cocoa growing has played a tremendous role in the transformation of lowland tropical landscapes over the past centuries and continues to do so (Schroth and Harvey 2007). Currently around 66% of cocoa production comes from Africa, 18% from Asia and 15% from the Americas (FAOSTAT 2016). Two African nations, Côte d'Ivoire and Ghana, produce almost half of the world's cocoa beans, with 1.445 million Mg (31.6% of global production) and 0.835 million Mg (18.2% of global production) in both countries, respectively, in 2014. Other large producers include Indonesia with 15% (775 thousand Mg), Nigeria 8% (366 thousand Mg), Cameroon 7% (275 thousand Mg) and Brazil 6% (256 thousand Mg) of global production (Fig. 23.1).

In West Africa, cocoa cultivation has been, relative to other agricultural activities, the leading sub-sector in economic growth and development (Duguma et al. 2001). In the last decades, cocoa has been also promoted as an alternative to production of coca (*Erythroxylum coca*) in various South American countries (Andres et al. 2016). In many countries, it is one of the most important cash crops, grown predominantly (80–90% of the global area of cultivation) by small-scale farmers and employs around 14 million workers worldwide (Duguma et al. 2001; ICCO 2012).

According to FAO data, the production and extension of cocoa growing have nearly doubled over the last two decades (FAOSTAT 2016). Between 1994 and 2013, production has increased from 2.673 to 4.586 million Mg grown on 5.760 and 10.012 million ha, respectively. It is, however, alarming that the increase of production was solely caused by an increase of cultivated area, not by increase of yields (world average yields stagnate at around 450 kg ha^{-1}). Growing demand for cocoa has been met by expanding the area under cultivation by almost 3% per year in the last decade (Andres et al. 2016).

There is no precise information on the extent of cocoa grown in agroforests, but rough estimation says that around 70% of cocoa is cultivated under various levels of shade (Gockowski and Sonwa 2011). Yet, growing cocoa in full-sun monocultures

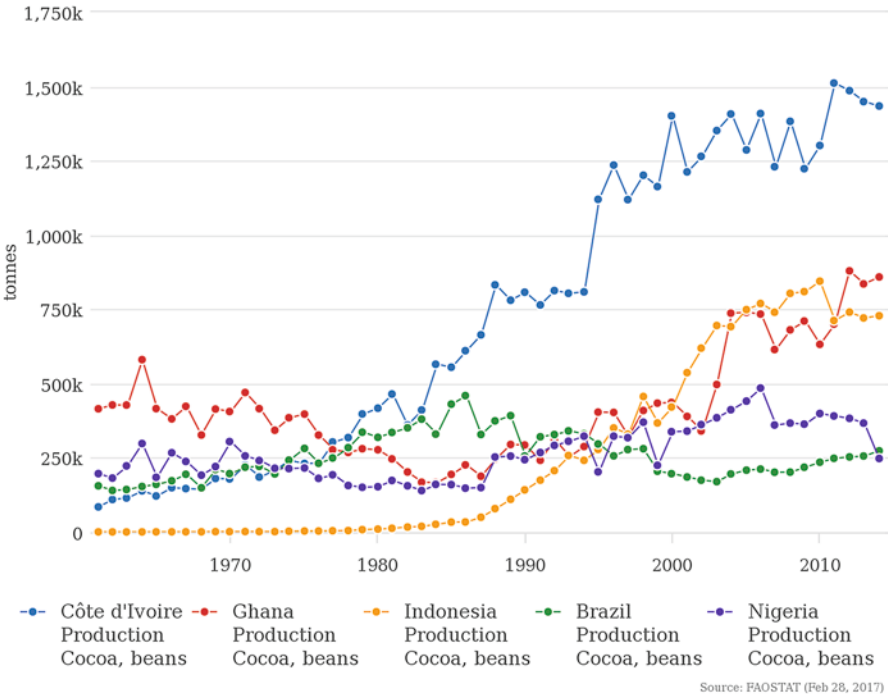

Fig. 23.1 Top five producers of cocoa beans until 2014 (FAOSTAT 2016)

is increasing, despite numerous problems associated with these systems (Tscharntke et al. 2011; Rice and Greenberg 2000). In Côte d'Ivoire, the largest producer worldwide, farmers currently prefer monoculture cocoa production, whereas in most American countries, agroforestry systems are a common practice (Andres et al. 2016). Efforts to increase yield have in many cocoa-producing countries resulted in loss of both shade levels and tree species richness (Vaast and Somarriba 2014). In Cameroon and Nigeria, cocoa agroforests still exhibit high levels of shade. In Ghana and Côte d'Ivoire, research has identified a long list of tree species that are claimed to be incompatible and of which their elimination from cocoa farms has consequently been encouraged, because they might serve as alternative hosts for pest and diseases (Asare 2006). Because of lower labour costs and higher short-term yields (Franzen and Mulder 2007), also in parts of Indonesia, full-sun cocoa is becoming a common cultivation practice (Belsky and Siebert 2003).

Due to increased demand, the pressure to step up production is likely to increase in the future, which, if contemporary farming systems will not be made more sustainable, may lead to more monocultures being established in forested areas (Schroth and Harvey 2007). However, many of the farmers and scientists recognize and claim that shade trees are crucial foremost to reducing both ecological and economic risks, including maintenance of soil fertility and moisture, weed suppression and pest and disease control, and play an important role in climate change adaption of cocoa cultivation (Franzen and Mulder 2007; Jacobi et al. 2013).

3 Management of Cocoa Agroforests

The natural habitat of cocoa trees is under closed-canopy tropical forests, commonly nutrient-rich alluvial soils (Wood and Lass 2001). In agroforests, this shade is provided by thinned native forest canopy, with cocoa seedlings planted in the cleared understorey, or through planted shade trees (Tscharntke et al. 2011). Rice and Greenberg (2000) described a spectrum of cocoa-producing strategies. At one end of this spectrum is 'rustic cocoa' where primary or secondary forests are thinned and cocoa is planted beneath the remaining canopy. On the other end, there is a 'planted shade' referring to systems where cocoa trees are intercropped with various amounts and diversities of fruit, commercial timber or fast-growing shade trees or other perennial corps, such as banana and plantains.

Cocoa plantation establishment is the easiest and cheapest within the tropical forest (Jagoret et al. 2015; Clough et al. 2009). Young cocoa plants need shade to avoid physiological stress arising from direct sun exposure, fertile soils and protection from competing weeds (Clough et al. 2009). Shade is thought to affect cocoa physiology as well as its physical environment, which affects its fitness and resistance to pests, diseases and other (a)biotic stress conditions (Rice and Greenberg 2000). Shade tree species richness can be very high as in the case of thinned forests or low as in the case of mono-species shade systems (e.g. including *Gliricidia sepium* in Central America and Indonesia). Shade provides numerous ecological benefits, and once removed, farmers become increasingly dependent on chemical inputs that may not always be affordable to them (Franzen and Mulder 2007).

The dominant practice of cocoa cultivation in the humid regions of West and Central Africa involves planting cocoa trees in secondary forest or forest fallow, selectively cleared and planted with various crops (Duguma et al. 2001). When land is cleared, certain indigenous fruits and medicinal and timber tree species (e.g. *Ricinodendron heudelotii*, *Cola nitida*, *Terminalia superba*, *Khaya ivorensis*) are deliberately retained for their economic value as well as to provide shade to the cocoa plants. The system is later enriched by planting additional tree crops, such as mango (*Mangifera indica*), African plum or pear (*Dacryodes edulis*), avocado (*Persea americana*), guava (*Psidium guajava*) and citruses (*Citrus* spp.), or valuable timber trees, such as mahogany (*Swietenia macrophylla*) or teak (*Tectona grandis*). As the cocoa trees and other components grow to maturity, the agroforest becomes a more diverse and structurally complex, closed-canopy multistrata system.

In America, cocoa farmers use popular agroforestry leguminous shade trees such as species of *Inga*, *Erythrina* and *Gliricidia*, and various palm species (e.g. coconut, *Bactris gasipaes*, and *Euterpe* spp.) (Vebrová et al. 2014; Andres et al. 2016) and plantain and banana (*Musa* spp.) are used for temporal shade during the first years of establishment. In Asia, the most commonly planted shade trees are *Gliricidia* spp., *Erythrina* spp., *Leucaena leucocephala* as well as other multipurpose trees (e.g. coconut and large variety of fruit trees) according to farmers' needs (Belsky and Siebert 2003; Rajab et al. 2016) (Table 23.1).

Table 23.1 Selected characteristics of cocoa agriculture and typical plant species of multistrata assemblages in different geographical regions

Geographical area and world cocoa production share[a]	South/Central America (14.8%)	West Africa (66.1%)	Southeast Asia (17.9%)
The main producers[a]	**Brazil, Ecuador, Dominican Republic, Colombia**	**Côte d'Ivoire, Ghana, Nigeria, Cameroon**	**Indonesia, Malaysia**
Illustrative photo of cocoa multistrata system in the region			
	Agroforestry system featuring cocoa and various timber and palm species in the Peruvian Amazon	*Cocoa multistrata system with oil palm and fruit trees in central Cameroon*	*Example of cocoa-fruit tree agroforesty from West Sumatra (durian is the dominant fruit species)*
Tree and palm upper layer[b]	*Bactris gasipaes* (food, shade)	*Ceiba pentandra* (fibre)	*Arenga pinnata* (food, fibre)
	Cedrela spp. (timber)	*Ficus* spp. (food, feed, timber)	*Artocarpus* spp. (food)
	Cocos nucifera (food, shade)	*Hevea brasiliensis* (latex)	*Cocos nucifera* (food, shade)
	Cordia alliodora (shade, timber)	*Irvingia gabonensis* (food)	*Durio zibethinus* (food)
	Dipteryx spp. (shade, timber)	*Khaya ivorensis* (timber)	*Hevea brasiliensis* (latex)
	Euterpe spp. (food)	*Milicia excelsa* (timber)	*Parkia* spp. (shade, food)
	Hevea spp. (latex, shade)	*Ricinodendron heudelotii* (food, medicine)	*Swietenia macrophylla* (timber)
	Spondias mombin (food, shade)	*Terminalia* spp. (timber)	*Tectona grandis* (timber)

(continued)

Table 23.1 (continued)

Geographical area and world cocoa production share[a]	South/Central America (14.8%)	West Africa (66.1%)	Southeast Asia (17.9%)
Shrub, lower tree and palm middle layer[b]	*Annona* spp. (food)	*Citrus* spp. (food)	*Citrus* spp. (food)
	Citrus spp. (food)	*Cola nitida*, *C. acuminata* (medicine)	*Erythrina* spp. (shade)
	Erythrina spp. (shade, timber)	*Dacryodes edulis* (food)	*Garcinia* spp. (fruit)
	Eugenia spp. (food)	*Elaeis guineensis* (edible oil)	*Gliricidia* spp. (shade)
	Gliricidia spp. (shade)	*Garcinia* spp. (food, medicine)	*Lansium parasiticum* (food)
	Inga spp. (food, shade)	*Mangifera indica* (food)	*Leucaena leucocephala* (shade)
	Mangifera indica (food)	*Persea americana* (food)	*Mangifera* spp. (food)
	Persea americana (food)	*Psidium guajava* (food)	*Nephelium lappaceum* (food)
	Pouteria spp. (food)	*Spathodea campanulata* (shade, medicine)	*Psidium guajava* (food)
	Theobroma bicolor, *T. grandiflorum* (food)	*Voacanga africana* (medicine, spiritual use)	*Syzygium* spp. (food)
Root, cover, climber and herbaceous layer[b]	*Ananas comosus* (food)	*Arachis hypogaea* (food)	*Ananas comosus* (food)
	Arachis hypogaea (food)	*Carica papaya* (food)	*Capsicum* spp. (food)
	Capsicum spp. (food, spice)	*Colocasia esculenta* (staple food)	*Carica papaya* (food)
	Carica papaya (food)	*Dioscorea* spp. (staple food)	*Colocasia esculenta* (staple food)
	Dioscorea spp. (staple food)	*Manihot esculenta* (staple food)	*Manihot esculenta* (food/staple food)
	Manihot esculenta (staple food)	*Musa* spp. (food/staple food)	*Musa* spp. (food)
	Musa spp. (food)	*Passiflora spp.* (food)	*Passiflora* spp. (food)
	Passiflora spp. (food)	*Vigna unguiculata* (staple food)	*Piper nigrum* (food)
	Piper nigrum (food)	*Xanthosoma* spp. (staple food)	*Xanthosoma* spp. (staple food)
	Plukenetia volubilis (edible oil)	*Zea mays* (staple food)	*Zea mays* (staple food)
	Saccharum officinarum (food)		various Zingiberaceae, e.g. *Zingiber*, *Etlingera*, *Curcuma* (food, medicine)
	Zea mays (staple food)		

Prevalent cocoa pest and diseases[c]	**Fungal diseases**	**Fungal diseases**	**Fungal diseases**
	Frosty pod rot (*Moniliophthora roreri*)	Black pod disease (*Phytophthora palmivora*, *P. megakarya*)	Black pod disease (*Phytophthora palmivora*)
	Witches' broom disease (*M. perniciosa*)		Vascular streak dieback (*Ceratobasidium theobromae*)
	Black pod disease (*Phytophthora palmivora*)		
	Insect pests	**Insect pests**	**Insect pests**
	Common mirid (*Monalonion dissimulatum*)	Mirids (e.g. *Sahlbergella singularis*, *Distantiella theobroma*)	Cocoa pod borer (*Conopomorpha cramerella*)
	Thrips (e.g. *Selenothrips rubrocinctus*)	**Virus**	Mirids (*Distantiella theobroma*, *Monalonion dissimulatum, Sahlbergella singularis* and *Helopeltis* spp.)
	Cocoa beetle (*Steirastoma breve*)	Cocoa swollen shoot virus (CSSV), transmitted by mealybugs	
Cocoa propagation[d]	Mostly hybrids but clonal cocoa is being increasingly used, predominantly grafted onto rootstock and rooted stakes of selected clones adapted to the local conditions	Hybrids which are being sexually propagated in seed gardens	Hybrids but also side- and top-grafted improved planting material is being increasingly used

(continued)

Table 23.1 (continued)

Geographical area and world cocoa production share[a]	South/Central America (14.8%)	West Africa (66.1%)	Southeast Asia (17.9%)
Prevalent cocoa genetic type[e]	All types (i.e. Upper Amazon Forastero, Lower Amazon Forastero, Criollo, Trinitario, Nacional and hybrids of aforementioned groups)	Hybrids, mostly of Amelonado	Hybrids, mostly of Trinitario
Average cocoa yields (2014)[a] kg ha^{-1}	424	432	412
Total area cultivated (2014)[a] M ha	1,704,759	6,770,367	1,830,377
Production quantity (2014)[a] Mg $year^{-1}$	722,849	2,921,757	753,611

[a] Based on FAO statistics 2014 (FAOSTAT 2017)

[b] Plant taxa are selected based on studies reviewed in the present chapter and are ordered alphabetically; the main plant uses are indicated in the brackets

[c] Source: Bailey and Meinhardt (2016)

[d] Sources: Vaast and Somarriba (2014); INGENIC (2009)

[e] Sources: Sounigo et al. (2005); Aikpokpodion (2012); Dinarti et al. (2015)

The major management requirements of cocoa agroforests include shade control, weeding (especially in the first years after establishment), pest and disease control, soil fertility maintenance, pruning and thinning of both cocoa trees and shade trees, regular pod harvesting and postharvest processing (Wessel 1987). Optimal growth and productivity are promoted by shading that allows 20–30% of sunlight to penetrate through the shade tree canopies (Duguma et al. 2001), especially for young cocoa trees. When cocoa trees mature, farmers sometimes try to intensify their plantations by removing shade trees to increase (short-term) yields. However, when cocoa trees age beyond 15–25 years in unshaded plantations, dwindling yields and increasing pressure from insect pests often lead farmers to abandon existing plantations (Johns 1999; Schroth et al. 2000; Arshad et al. 2015). Thus, shade removal has negative long-term effects that jeopardize sustainability of cocoa production and reduces ecological resilience (Rice and Greenberg 2000; Tscharntke et al. 2011; Vaast and Somarriba 2014; Rajab et al. 2016; Andres et al. 2016). Improving cocoa yield does not necessarily require shade removal and agrochemical inputs. Good agricultural practices such as regular pruning can reduce pests and increase yield (Clay 2004). Well-managed and well-maintained cocoa agroforests have a potential to remain productive and environmentally sustainable for up to 50 years (Duguma et al. 2001). Some authors highlighted continuous production of cocoa agroforests up to even 80–100 years (Bentley et al. 2004). Retaining high shade levels in young cocoa plantations with a stepwise increase in shade tree thinning and pruning when cocoa trees grow older is a realistic and sustainable management strategy (Tscharntke et al. 2011).

Cocoa production in monoculture usually requires large amounts of agrochemicals and improved genetic material specifically developed to fit in full-sun systems. Under optimal management, cocoa yield is higher in full-sun monoculture, at least during the first cocoa production years. However, intensive crop management is hardly feasible for most small-scale farmers (van der Wolf et al. 2016). By contrast, in agroforests, producers often aim at substituting external inputs by system-inherent resources (Andres et al. 2016). Examples include nutrient recycling and inputs by shade tree pruning and pest control by natural predators.

In the long term, the cocoa yield gap (i.e. the difference between the current low average of 450 kg per ha per year and the potential yield of 3,000 kg per ha) might be closed by addressing the limiting factors with sustainable, yield-increasing management practices. As soil nutrient content in many cocoa-growing regions is poor, an obvious way next to the balanced shade, cocoa pruning and good sanitary conditions is to fulfil cocoa nutritional needs through fertilization (van Vliet et al. 2015). The use of organic fertilizers and the inclusion of nitrogen-fixing trees (or possibly also N-fixing cover crops in some cases) can greatly contribute to nutrient availability in smallholder cocoa production systems. Organic residues, contrasting to standard NPK fertilizers, replenish also other overlooked nutrients such as Ca, Mg and microelements. Furthermore, they maintain soil organic matter, which is favourable for cocoa production (van Vliet et al. 2015).

4 Could Agroforestry and Proper Management Prevent Boom-and-bust Cycle?

Regional boom-and-bust cycles represent the common pattern in global cocoa production, which has caused large areas of forest to be converted to cocoa agroforestry systems or monocultures (Clough et al. 2009). Cocoa production has contributed to the destruction of the Atlantic Rainforest in Brazil, African forests in Ivory Coast and Nigeria and parts of primary forest in Sulawesi and Sumatra in Indonesia (Franzen and Mulder 2007). The dynamics of land under cocoa cultivation, conversion and abandonment is hard to be captured. However, Clough et al. (2009) based on FAO statistics indicated that there is much larger conversion of forestland to cocoa than appears in net area under cultivation.

Initially, the establishment of production in a forest-like environment enables both the maintenance of high biodiversity compared to other agricultural land uses (Rice and Greenberg 2000). During the production cycle, cocoa trees form a lower-strata closed canopy themselves and become less dependent on shade trees that can then be removed without immediate deleterious effects. Aging cocoa trees (about 15–20 years) tend to have stagnating or decreasing yield; therefore, farmers try to increase the yield by elimination of remaining shade trees (Clough et al. 2009). With increasing cocoa tree age along with outbreaks of pests and diseases, cocoa cultivation turns into the bust cycle, which drives large-scale cocoa abandonment (Panlibuton and Meyer 2004). As new pioneer fronts are opened to meet the demands of the cocoa sector, the cycles successively repeat in new forestland (Clough et al. 2009). Alternatively, cultivation of cocoa plantations shifts to intensive and often environmentally devastating single-strata agricultural land-use systems such as oil palm plantations, as is the case in Malaysia (Basri Wahid et al. 2006; Fitzherbert et al. 2008), or bananas in Costa Rica (Dahlquist et al. 2007). Cocoa agroforests can remain productive for a relatively longer period than monocrop cocoa plantations, as e.g. shown by system dynamic models favouring more biodiverse cocoa agroforests, while demonstrating rapid failure of intensified cocoa production on example of Malaysia (Arshad et al. 2015). However long-term studies from other countries are still missing in scientific literature.

Shade reduction increases yield but also physiological stress (Vernon 1967). The most severe production constraint and major cause of bust of cocoa production is the occurrence of pests and diseases that can cause yield losses of up to 80% (Duguma et al. 2001). The most prevalent pest and diseases in the main cocoa growing areas are given in Table 23.1. Reduced biodiversity in full-sun systems means less resistance to pests, usually caused by decrease of natural predator populations (Franzen and Mulder 2007). According to farmers in Alto Beni (Bolivia), incidences of pests and diseases are more intense and frequent in monocultures than in agroforests (Jacobi et al. 2013), but the results from other studies are not such promising. The prevalence of pest and diseases in all systems is highly affected by the age of the cropping system. Farmers often shift from areas where they cannot cope with high prevalence of pest and disease to new pest- and disease-free and fertile pioneer fronts. The Bolivian case study showed that cocoa trees in monocultures developed more pods but also exhibit higher incidences of pests and diseases, eventually leading to higher losses of pods before harvest (Andres et al. 2016). In Costa Rica, it was found that under more intensive and more complex shade in terms of diversity and spatial distribution of shade trees in cocoa plantations, there is less frosty pod rot incidence (Bieng et al. 2013; Gidoin et al. 2014). Enhancing air circulation through regular weeding, pruning and thinning of shade trees helps to control pests and diseases (Duguma et al. 2001). Proper pruning of cocoa trees is a crucial intervention influencing the regulation of pests and diseases (Franzen and Mulder 2007) and increasing yield (Wood and Lass 2001). Unfortunately, many farmers, lacking the equipment and workforce, face difficulties in pruning their cocoa or shade trees (Andres et al. 2016) and are reluctant to conduct heavy pruning (Clough et al. 2009). As a result, rather than pruning shade trees, they often prefer to cut them down and leave the cocoa trees without pruning. However, pruning the shade trees to manage shade intensity and rehabilitation pruning of cocoa trees would be a more effective practice (Andres et al. 2016), decreasing relative humidity in the system and in turn creating less favourable conditions for some pests and diseases (Smith Dumont et al. 2014). However, it is often challenging to identify adequate shade levels and tree species compositions that minimize damage from pests and diseases while ensuring favourable growing conditions for cocoa trees (Andres et al. 2016). Moreover, the initial mismanagement such as inappropriate planting distances and inadequate pruning during the first few years is common among the inexperienced cocoa farmers and makes corrective management extremely difficult in later production stages (Clough et al. 2009). According to Zhang and Motilal (2016), phytosanitation, such as removal and burial of infected cocoa pods, leaves, branches and weeds, is one of the most cost-effective method for reducing pests and diseases for smallholders. Research in Peru found that weekly removal of pods infected with black pod disease decreased incidence of the disease by 35–66% and increased yield by 26–36% (Soberanis et al. 1999).

Cocoa management practices are also highly influenced by governmental and non-governmental actors. Governmental policies have often favoured large-scale intensive plantations over the more diverse farms of smallholders (Rice and Greenberg 2000). Among the reasons were that large-scale planters paid more for their land, used more expensive labour and had higher fixed and working capital costs compared to the smallholders. Nowadays, overwhelming majority of produced cocoa is in the hands of smallholders and those in need of technical support to sustainably intensify and maintain existing cocoa farms. Indonesia is an interesting example, where, as opposed to the past situation in neighbouring Malaysia, the clear majority of cocoa farmers are smallholders. Land under cocoa cultivation in Indonesia is still expanding, and recently, the country has surpassed Ghana in the land area under cocoa cultivation to become the second largest producer in 2014 (FAOSTAT 2016). Nevertheless, the productivity and production are rather on decline after 2010 (Fig. 23.1), and sector is experiencing shift of farmers towards other crops particularly in the last years. Clough et al. (2009) questioned the future of cocoa in Indonesia, especially considering the failure of unsustainably intensified

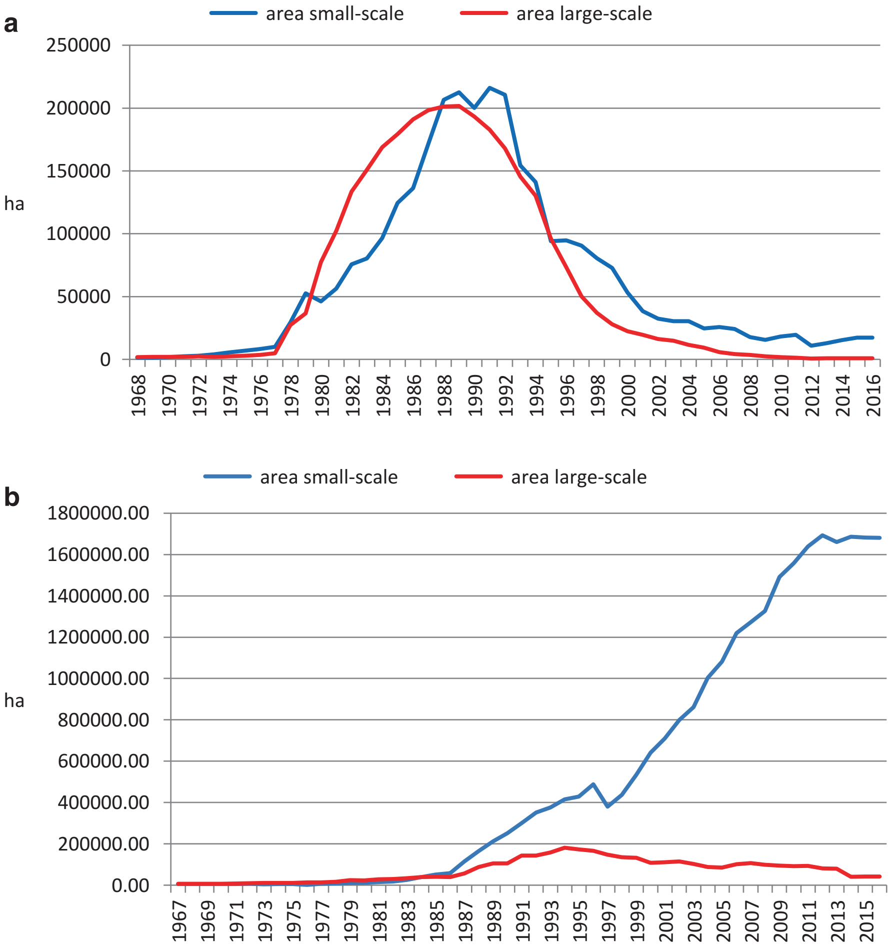

Fig. 23.2 Trajectory of land area under cocoa cultivation in Malaysia (**a**) and Indonesia (**b**) (Statistics of Indonesia 2015, Statistics of Malaysia 2016)

production in neighbouring Malaysia as the lessons learned. The statistics of Indonesia and Malaysia, which distinguish size of cocoa holdings, show that the land area under cocoa production in these countries exhibits striking differences (Fig. 23.2).

First, the Indonesian cocoa is exclusively in the hands of smallholders, and second, the cocoa cultivation in Indonesia is increasing at small-scale level. Over the past few years, however, the cultivation area in Indonesia has stagnated. This most likely indicates no significant encroachment of the production to the new forestlands. Yet, to prevent it and to sustain cocoa production in the country, the productivity must be increased. The national platform – Cocoa Sustainability Partnership (CSP) – came up with targets of doubling farmers' productivity through trainings and increasing access to new planting material and fertilizers, to ensure profitable business, motivating young cocoa farmers to remain in the sector, and to prevent shifting to other crops (CSP 2013). The strategy was implemented since in the current situation; profit range per hectare per year is much higher for palm oil and rubber tree than for cocoa.

A promising contemporary large-scale cocoa project could be the Sustainable Cocoa Production Program (SCPP) in Indonesia. SCPP is a large public-private partnership development project, designed and implemented by the Swiss Foundation for Technical Cooperation (Swisscontact 2016). The project aims to facilitate capacity-building measures for 130,000 smallholder cocoa farmers. The program has a holistic approach and facilitates and implements activities in the social, economic and environmental dimensions while promoting full cocoa value chain transparency and traceability. The keystone activity is the training in good agricultural practices – cocoa management – but the program also recently integrated climate-smart agriculture and environmentally friendly practices, where importance of shade trees and biodiversity is being raised and monitoring of shade trees and carbon footprint is being conducted. Apart from development of farmers' training centres, the project focuses also on developing cocoa nurseries and clonal gardens ensuring that farmers are better linked to improved planting material, as the aging cocoa trees next to the soil degradation are one of the main constrains in the sector. The program monitoring reported an increase in farmer's productivity from 429 kg ha^{-1} to 721 kg ha^{-1} (Swisscontact 2016).

5 Cocoa Genetic Diversity and its Potential

The sustainability and stability of the world's cocoa production depend among other factors and also on its proper germplasm management. One of the requirements to avoid the boom-and-bust cycle and its adverse consequences is the use of germplasm with a broad genetic base to breed new varieties with increased disease and pest resistance, desirable quality traits and the ability to adapt to changing environments (Zhang and Motilal 2016). The advantage that cocoa has in comparison with other major crops is the existence of a large natural gene pool in the form of wild populations in the Amazonian rainforest, which are evolving to be possibly resistant to various pathogens and can be readily involved in breeding programs and crossed with cultivated cocoa (Eskes and Efron 2006; Zhang et al. 2006). As a result, knowledge on and conservation of genetic diversity and population structure of local cocoa germplasm (including wild in the regions of origin) is critical in enhancing cocoa cultivation sustainability (Aikpokpodion 2012).

The introduction of cocoa cultivation outside the Americas started at the end of the seventeenth century, and from then onwards, the crop has spread throughout the tropics (Bartley 2005). Throughout the history of cocoa cultivation, the populations were periodically decimated by pest and disease outbreaks, which led to a shift of the centre of cocoa production to new cultivation areas, whereby only a small fraction of the available germplasm was moved to new sites. In spite of the availability of the diverse natural gene pool, only a small fraction of the wild germplasm, collected during the 1930s–1940s from the Upper Amazon of Ecuador and Peru, has been used in breeding (Wood and Lass 2001), and although these efforts made a significant impact in terms of resistance to diseases (especially to witches' broom disease) and adaptability, little new variability was added to cocoa breeding programs in the last 70 years (Zhang and Motilal 2016).

Several studies were conducted in West Africa to assess the level of genetic diversity in breeders' and farmers' collections as well as in parental collections, which include the original clones brought to Africa around the middle of the nineteenth century and used in breeding (Opoku et al. 2007; Tahi et al. 2008; Efombagn et al. 2009; Pokou et al. 2009; Aikpokpodion et al. 2010; Aikpokpodion 2012). Generally, the first cocoa introduced to Africa was of the Amelonado type (Lower Amazon Forastero according to traditional classification), with later addition of hybrids from Trinidad (Efombagn et al. 2008), which were used as parents for the first biparental crosses (Opoku et al. 2007). Various studies have shown that Lower Amazon Forastero or Amelonado accessions are mostly homozygous with low genetic diversity (N'Goran et al. 1994; Motamayor and Lanaud 2002; Motamayor et al. 2003). Furthermore, the accessions belonging to this group were generally highly susceptible to cocoa swollen shoot virus (CSSV). The local cocoa germplasm has been broadened in the 1950s and 1960s by the introduction of clones from the Upper Amazon region (belonging mainly to the Iquitos, Contamana, Nanay and Maranon genetic clusters presented by Motamayor et al. 2008) as a response to CSSV epidemics in Ghana, Togo and Nigeria, which almost destroyed the complete cocoa industry in that area (Efombagn et al. 2008; Aikpokpodion 2012). The cocoa varieties from the Upper Amazon region were collected in the 1930s during an expedition to Peru and Ecuador in search for natural germplasm with increased resistance to diseases (Wood and Lass 2001). This introduction became a basis for the development of modern cocoa varieties in West Africa (Opoku et al. 2007).

To assess the genetic diversity of cocoa trees in Ghana, Opoku et al. (2007) analysed 377 accessions including farmers' accessions, breeders' collections and parental clones from all cocoa-growing regions of Ghana. It was found that average genetic diversity in all populations was relatively high. However, the diversity of parental clones and breeders' collections was significantly higher than that among farmers' accessions. Apparently, farmers have a low preference for breeders' germplasm. Socioeconomic data recorded during collection missions of Opoku et al. (2006) confirmed these findings. Cluster analysis separated the accessions from western regions in Ghana from other populations, indicating that breeders' germplasm was adopted to an even lesser extent in remote areas. It was confirmed that despite the availability of improved germplasm, a significant number of farmers still select planting material from their own or neighbouring farms. This can have a deleterious impact on Ghanaian cocoa populations and production (Opoku et al. 2007).

A similar situation occurs in Cameroon, where cocoa growers are presently not very satisfied with the prevailing hybrid varieties, because of high tree mortality and the reported higher susceptibility to disease and pests. In general, the farmers harvest cocoa pods from their own trees for cocoa propagation. Therefore, Efombagn et al. (2006) assessed genetic diversity of more than 250 cocoa accessions in farmers' fields, seed gardens and on-station cocoa collections. The results revealed two main genetic groups in farmer collections corresponding to their geographical origin. The first group (central and south provinces) was closely related to the Amelonado type from the seed gardens, and the second group (east province) was clustered together with local hybrids. Although Upper Amazon clones were found to be included in breeders' collections, their presence was not verified on farmers' fields, which is unfortunate since these clones are known to be resistant to black pod disease. Moreover, the values of genetic parameters obtained in this study indicated that the genetic basis of cultivated cocoa in southern Cameroon was narrow. Further study assessed the genetic diversity and structure of farm and gene bank accessions of cocoa in Cameroon (Efombagn et al. 2008), and the results revealed quite a high gene diversity in both groups, which can be explained by the large variation of cocoa introduced in Cameroon at the beginning of the twentieth century (Bartley 2005), but confirmed the narrow genetic base of used germplasm. Only a very small proportion (3%) of genes contained in the farmers' accessions originated from the varieties known for resistance to diseases, indicating the need for breeding new varieties with increased yield, resistance and quality, as well as the necessity of bringing new genotypes to the breeding programs.

If we look to Asia, Indonesia used to grow hybrid cocoa varieties from Trinidad before the 1950s (Bartley 2005). However, these varieties lacked resistance to cocoa diseases and pests, especially to vascular streak dieback (VSD), which led to breeding efforts using clones from the Upper Amazon (Dinarti et al. 2015). This led to development of new germplasm tolerant to BPR and VSD, which contributed to the rapid expansion of cocoa production in Indonesia over several decades (Susilo et al. 2009). However, production increase in Indonesia was largely due to expansion of cultivated area. Lack of improved varieties is still emphasized as one of the main production hindrance of cocoa production in Indonesia (Perdewa and Shively 2009; Ruf and Yoddang 2010). Genotypes resistant to VSD and BPR have been identified, but delivery of the appropriate genetic material to farmers' fields remains a major challenge (McMahon et al. 2009; Susilo et al. 2009).

Dinarti et al. (2015) analysed 53 farmers' accessions from Sulawesi and 153 reference cocoa clones with known genetic identities. The results showed that the overall scope of genetic diversity in the farmer selections accounts for only a small fraction of the available germplasm groups in the reference clones. Moreover, the revealed parentage background of farmers' accessions was mainly limited to a few clones from the Upper Amazon. The resistant Scavina clones, which have been consistently used in breeding program and seed gardens in Indonesia as well, had almost no impact on farmers' germplasm (Susilo et al. 2009). This discrepancy can be explained by limited access of the farmers to improved planting material and also by their strong preference for varieties with larger seed size, which are priced higher in Indonesia (Dinarti et al. 2015). Farmers may also have preferred clones with shorter pod development period, clones producing pods continuously all year round and clones with high yielding potential.

All those studies confirmed that there is still large potential of the use of wide genetic base of cacao found in the Amazon region, especially for breeding varieties resistant to various diseases. Nevertheless, there has been no major advance in development of resistant varieties in the last decades (Zhang et al. 2011). And even when those varieties exist, they have not been yet adopted and utilized in the main cocoa-growing regions of the world. Meanwhile, the cocoa sector worldwide must control pests and diseases by agricultural practices. Conventional pesticides are not commonly available to smallholder cocoa farmers due to their high price (Duguma et al. 2001) and their utilization carries many risks to human health as well as the environment (Avelino et al. 2011). Other practices that can be used in cocoa production are based on integrated pest and disease management and agroforestry that favour antagonism or microclimate conditions that reduce incidence of pests and diseases (Bos et al. 2007; Konam et al. 2008).

6 (Agro)biodiversity in Cocoa Agroforests

Agricultural biodiversity encompasses a broad array of biotic components such as raised animals, cultivated crops, wild useful plants and crop wild relatives but also pollinators, symbionts, pests and soil microorganisms (FAO 2011). In this part of the review, we focus on cocoa-associated diversity of plants useful to humans (whether planted or tolerated wild plants). Multistrata cocoa agroforestry preserves and utilizes a high level of agrobiodiversity (see Table 23.1, for the most common species) as it sustains or incorporates additional species into the land-use system. The mutual reinforcement of agrobiodiversity and agroforestry, and the contribution they add to sustainable production, livelihoods and environment, has been recently recognized (Atta-Krah et al. 2004).

It is known that farmers retain useful trees in the system predominantly for valuable products (e.g. food, medicine, fodder, fuel, various materials) and for perceived ecosystem services such as shade, wind protection and soil fertility replenishment. Certain trees are also preserved because of their sociocultural importance (i.e. sacred trees or trees with aesthetic value). Farmers also frequently intercrop cocoa with a wide range of annual (e.g. maize, groundnut) and perennial (e.g. cassava, banana) crops in early years of establishment (Schroth et al. 2004). As a result, this plant management is turning into the multistrata system with high agrobiodiversity in a few years after the establishment (Ruf and Schroth 2004). The species assemblage changes according to the age of cocoa trees and density of the canopy.

Certain cocoa multistrata agroforestry are of very high diversity, such as Brazilian *cabruca* system, where on average 101 tree species were found per 3 ha plot, totalling 293 species found on 15 ha (Sambuichi and Haridasan 2007). Other example is cocoa agroforestry in Cameroon, where 206 tree species were documented in 60 agroforests covering 9.1 ha in total. Many of those species were important resources of products (particularly food), services and income for the local farmers (Sonwa et al. 2007). Beside common crop species like oil palm, bananas and plantains, they included local multipurpose species, such as *Dacryodes edulis*. Authors demonstrated a shift of preferences from native to exotic species with increasing market access and land-use intensity. In Bolivia, a study on tree diversity found 96 tree species measured by 48 × 48 m plots on 8 cocoa agroforestry plantations in Alto Beni (Jacobi et al. 2014).

Farmers valued income from timber, better water balance and soil quality and the positive effect of shade on cocoa trees and working conditions (Jacobi et al. 2014). In homegardens of Central Sulawesi, where cocoa and coffee are important cash crops, Kehlenbeck and Maass (2004) found 149 crop species in just 30 smallholder homegardens. Jagoret et al. (2014) pointed out that not many studies on agroforestry consider the use value (cultural importance) of the associated agrobiodiversity. Jagoret et al. (2014) quantified the usefulness of agrobiodiversity in 50 cocoa agroforests in three sites of central Cameroon. For all species inventoried (123 species), 81% had from one to seven different uses. Authors concluded that majority of species are useful, and even though some species do not possess a high economic value, they are of vital importance for farmers. In Cameroon, agroforests have been cultivated for over a century, and numerous cocoa farms and plantations are still productive at age of over 40 years (Jagoret et al. 2011). Authors linked long-term sustainability, including stable cocoa yields in the absence of additional mineral fertilization, with a high degree of agrobiodiversity. A similar pattern of long-term diverse and continuously producing agroforestry is the Brazilian *cabruca* system (Johns 1999).

In their review of Central American cocoa agroforestry systems, Cerda et al. (2014) found that plants and trees in the multistrata cocoa agroforestry produce a diversity of fruit and timber tree species that can generate relevant amount of cash income and provide high value for household consumption at low costs, contributing to food security and family income, sometimes even more than from the cocoa itself. In the Peruvian Amazon, Vebrová et al. (2014) found tree species richness and diversity in cocoa agroforests much lower than in primary forest but comparable to secondary forests. Most of the trees occurring in agroforests were native multipurpose trees having clear productive function, such as fruit, timber, firewood, thatching or medicine.

Trees sustained after the clearing of the forest are predominantly native trees. Those that farmers add by planting into the system are often useful exotic species. They are of significant economic value for the farmers, and despite preference of native species by conservationists, they might also contribute to socioecological resilience. According to Guariguata et al. (2012), through natural selection and conscious or unconscious human manipulation, some exotic trees have developed into landraces with unique adaptive and productive characteristics that are esteemed by their custodian farmers. Smallholder agroforestry farmers play a crucial role in maintaining and conserving tree diversity *circa situm* (Dawson et al. 2013). Farmers' role in conservation of perennial crops is particularly important due to broad diversity of trees and challenges faced in *ex situ* conservation of woody species.

Incorporating agrobiodiversity of trees, crops and animals is known to increase the efficiency of farming systems and strengthen ecological resilience, when different components occupy complementary niches and react differently to biotic and abiotic stress (Steffan-Dewenter et al. 2007; Franzen and Mulder 2007). Diversity of trees in farmland also support populations of the insects, birds and other organisms needed for crop pollination and biological pest control, raising up crop productivity on return (Ricketts et al. 2004; Harvey and Gonzalez 2007; Tscharntke et al. 2008). Tscharntke et al. (2011) gave an example of the continuum of reducing pesticide spraying, which protects functional agrobiodiversity such as antagonists of pests and diseases and pollinating midges, which is resulting in higher yields of the cocoa. This issue has been emphasized by the research showing that successful pollination plays a more important role in the cocoa yield than the availability of natural resources in the cropping system (Groeneveld et al. 2010).

From the smallholder perspective, diversification is a livelihood strategy as the reliance solely on one crop commodity bears immediate risks due to drop prices and spread of pest and diseases or from natural calamities. As a responsive capacity to the cocoa drop prices in Cameroon (in 1987), farmers diversified cocoa farms by developing a multistrata system comprised of 189 tree species with food products and with 35 timber species per hectare (Gockowski and Dury 1999). The fact that farmers actively retain or introduce agrobiodiversity into the cocoa agroforests is a rational step towards economical (Cerda et al. 2014) and socioecological resilience (Franzen and Mulder 2007). Diverse agroforestry systems have also shown to reduce the pressure on surrounding natural forest resources (Murniati and Gintings 2001).

Multistrata systems possess particularly high diversity of fruits and other food products which form part of the local food system. Those resources contribute to the local peoples' diets with important nutrients, yet they have rather been overlooked by the research and policy (Powell et al. 2015). Contribution of agroforestry products towards diet and nutrition waits to be assessed. Researchers found a positive relation between tree cover (forests and agroforests) and dietary quality of the local inhabitants in Africa (Ickowitz et al. 2014) and Indonesia (Ickowitz et al. 2016). Due to increasing population and dwindling forest resources, agroforestry products are likely to play a crucial role in future rural community income and food security (Leakey et al. 2005). Finally, with diversity of trees, traditional knowledge systems of the local farmers are associated (Berkes et al. 1995; van der Wolf et al. 2016). These knowledge systems have become recognized essential in the context of biodiversity conservation, sustainable development as well as ensuring livelihood and resilience of the local people (Berkes et al. 2000).

If we look at the potential of cocoa agroforest for biodiversity conservation in general, we have to first realize that the main cocoa-producing areas coincide with the world's tropical biodiversity hotspots (Myers et al. 2000; Clough et al. 2009). A major challenge consequently is how to balance agricultural expansion with strategies for natural resource conservation (Asare 2006). Cocoa grown under the canopy of original forest is considered the most environmentally sound form of production, and shade systems have been shown to have higher biodiversity than full-sun systems (Franzen and Mulder 2007). Cocoa agroforestry further has the capacity of conserving some of the original forest faunal diversity, such as that of beetles (Harvey et al. 2006; Bos et al. 2007), ants (Bos et al. 2007; Delabie et al. 2007; Bisseleua et al. 2009), spiders (Stenchly et al. 2012), frogs and lizards (Faria et al. 2007), birds (Harvey and Gonzalez 2007; Van Bael et al. 2007), bats (Harvey and Gonzalez 2007) and terrestrial mammals (Harvey et al. 2006; Vaughan et al. 2007). The latter conservation capacity is mostly induced by the complex vegetation structure in cocoa agroforestry systems. In general, both plant and animal diversity within cocoa agroforests is greater than those of other agricultural land uses but lower than in the original undisturbed forest habitat (Donald 2004; Schroth and Harvey 2007). Rustic shade cocoa production systems do not have the same biodiversity benefits as undisturbed forest habitat (Siebert 2002; Clay 2004; Rolim and Chiarello 2004), but research suggests that they are ecologically preferable to other land uses (Franzen and Mulder 2007).

However, these positive effects are greatly influenced by the adequate management (Clough et al. 2009) as modern, intensified plantations deliver few advantages in terms of conservation when compared to traditional, shaded cultivation (Bhagwat et al. 2008).

Cocoa agroforests can create forest-like habitats, which harbour tropical biodiversity in rapidly degrading landscapes (Greenberg et al. 2000). This is particularly true in fragmented landscapes, where cocoa agroforests have been noted to provide habitat and resources for plant and animal species and maintained connectivity between different land uses (Asare 2006). Shaded cocoa can create important buffer zones around forest reserves, reducing edge effects and increasing interconnectivity among habitats (Tscharntke et al. 2011). In spite of these potentials, there have only been a few attempts to use cocoa agroforestry as a large-scale conservation instrument in tropical countries (Asare 2006).

7 Soil and Water Conservation in Cocoa Agroforests

The agroforests offer many environmental benefits to the soil's chemical, physical and biological properties. In general, they have a positive impact on belowground carbon stock, which is related to better conditions from both chemical (availability of (macro-)nutrients) and physical (better aggregates composition and thus faster water infiltration) points of view. Shading of tree canopy reduces adverse climatic effects and mitigates soil erosion. We tried to summarize recent knowledge of cocoa agroforest functions related to soil environment and soil and water conservation, especially in comparison with (i) monoculture agrosystems (as less natural systems) and (ii) primary/secondary forests (representing more natural systems).

Concerning soil nutrient status and soil reaction, many recent studies indicate the same or even slightly higher levels of soil Mg and Ca contents for certain types of shaded cocoa (i.e. Alfaia et al. 2004; Owusu-Sekyere et al. 2006; Gama-Rodrigues et al. 2010; Dawoe et al. 2013) in comparison with original baseline that was natural forest. It can be explained by burning of original biomass when establishing cocoa (Alfaia et al. 2004); nevertheless, excessive burning increases soil acidity and the loss of soil carbon and nitrogen (Celedón 2006; Zermeño-Hernández et al. 2015 in Zermeño-Hernández et al. 2016). In contrast to agroforests, in case of full-sun cocoa plantations in Côte d'Ivoire, deteriorations of Mg and Ca were recorded (Tondoh et al. 2015). A study of Dawoe et al. (2014) shows approximately similar levels of K in soils comparing cocoa agroforests and primary forests, whereas others highlight its significant decrease in cocoa agroforests (Asare 2006; Owusu-Sekyere et al. 2006; Ofori-Frimpong et al. 2007). However, this depletion is much higher in case of cocoa monocultures (Ofori-Frimpong et al. 2007; Tondoh et al. 2015). Similarly, P that represents an important ecological limit in tropical soils in general (Oberson et al. 2006) is considered to be even more depleted from soil by cutting primary forests and establishment of cocoa agroforests by some authors (Alfaia et al. 2004; Asare 2006; Ofori-Frimpong et al. 2007; Dawoe et al. 2013), whereas others indicated its increase (Owusu-Sekyere et al. 2006; Gama-Rogrigues et al. 2014) or equal levels (Dawoe et al. 2013) in topsoil. On the other hand, the P deterioration rate was much higher in case of full-sun plantations (Ofori-Frimpong et al. 2007; Tondoh et al. 2015) in reference to primary forests and cocoa agroforests. Indeed, researches from Brazil (Zaia et al. 2008) have shown that phosphorus balances depend strongly upon P fractionation: in the Oxisol group, in soils under cocoa agrosystems, the total organic P, microbial P and plant-available P contents were higher and the labile organic P lower than in the soil under natural forest. The dynamics of particular P forms also differs among soil types (soil groups, e.g. Inceptisols versus Oxisols). Based on this review, it is obvious that the role and dynamics of phosphorus in agro(forestry) systems are very complex and management practices – including fertilizers and other amendments – must be tailored for habitat and place.

Cation exchange capacity (CEC) and soil pH are closely related parameters, also in narrow link to nutrient status and mainly soil organic matter quantity and quality. Table 23.2 summarizes the results of two long-term studies assessing the chemical and physical soil parameter changes on transition from natural forest to (i) cocoa agroforestry systems (Dawoe et al. 2013) and (ii) cocoa full-sun plantations (Tondoh et al. 2015). The changes in soil parameters are expressed by degradation index that clearly shows long-term increase in cocoa agroforests and decrease in full-sun cocoa plantations.

7.1 Carbon Stock and Sequestration

Carbon stock in tropical ecosystem is mainly in above-ground biomass. However, the carbon sink belowground has great importance. Dawoe et al. (2014) state that in natural forest, belowground carbon stock represents approx. 18% of total carbon, which is in agreement with other studies. Absolute values differ among studies/territories: in Cameroon natural forests have about 273–289 Mg ha^{-1} of total carbon,

Table 23.2 Degradation indices (DI in %) for 0–10 cm soil layer along a chronosequence of cocoa fields following conversion of natural forest to (a) cocoa agroforestry systems (Dawoe et al. 2014) and (b) to full-sun cocoa plantations (Tondoh et al. 2015)

Cocoa AF (Dawoe et al. 2014)				Cocoa full-sun (Tondoh et al. 2015)			
Parameter	3 years	15 years	30 years	Parameter	5 years	10 years	20 years
Bulk density (g.cm^{-3})	−17.8	−24.8	−29.7	Bulk density	+18.2	+8.7	+22.0
C (%)	−28.1	−15.3	−13.6	C (g.kg^{-1})	−28.9	−43.5	−39.1
Ntot (%)	−12.0	−33.3	−12.0	Ntot (g.kg^{-1})	−27.7	−40.0	−31.0
CEC (cmol.kg^{-1})	−2.3	+30.1	+43.7	CEC (cmol.kg^{-1})	−13.3	−21.0	−21.0
Base saturation (%)	+0.7	+0.4	−0.5		N.D.	N.D.	N.D.
Available P (mg.kg^{-1})	+12.1	+5.13	−37.7	Available P (mg.kg^{-1})	+38.4	+41.4	+22.4
K (cmol.kg^{-1})	+55.0	+15.0	+67.5	K (cmolc.kg^{-1})	−12.1	−24.8	−14.1
Ca (cmol.kg^{-1})	−13.4	+15.0	+14.0	Ca (cmolc.kg^{-1})	−15.2	−23.2	−09.1
Mg (cmol.kg^{-1})	+23.0	+72.4	+116	Mg (cmolc.kg^{-1})	−5.3	−34.9	−24.5
Porosity %	−11.0	−15.2	−18.3		N.D.	N.D.	N.D.
Microbial biomass (mg.kg^{-1})	−61.8	+11.6	−18.5		N.D.	N.D.	N.D.
DI cumulative	−55.6	+61	+110.9		−46	−137.3	−94.3
Only param. assessed in both studies	+16.5	+64.23	+148.2				

DI is difference (%) between mean values of individual soil properties under cocoa land-use chronosequences and the baseline values of respective soil properties under the natural forest. N.D. Data not measured

whereas Dawoe et al. (2014) show approx. 255 Mg ha^{-1} in primary forest of Ghana and similar values – approx. 260 Mg ha^{-1} is available from Brazil (Gama-Rodrigues et al. 2011).

In contrast to this, in cocoa agroforestry systems, the total carbon stock is about 117 Mg ha^{-1} as averaged for the whole Central America (Dawoe et al. 2014) with wide differences among plots (46–333 Mg C ha^{-1}), while approximately one half (51%) of this amount is attributed to soil organic carbon that represents a fare significant part. Gama-Rodrigues et al. (2011) state SOC up to 302 Mg ha^{-1} which is a (not stat. significant) higher level than in Brazilian natural forest. Indeed, SOC in cocoa AFS in Indonesia have been shown to differ also only slightly from those of primary forests [Hertel et al. (2009) in Tscharntke et al. 2011]. It exhibits high importance of cocoa AFS for carbon sequestration and mitigation of climate change.

Although many studies dealing with carbon sink and sequestration have been published, they are mostly about comparing several habitats and land-use systems among them (e.g. Monroe et al. 2016). There has been a lack of long-term study of changes on transition between land-use types for a long time.

Dawoe et al. (2014) published a study evaluating changes in soil properties during 30 years of transition from primary forest to cocoa agroforestry. Concentrations and stocks of soil organic carbon (SOC) and total N decreased significantly in the top 0–10 and 10–20 cm soil depths in the first stages after primary forest cutting. However, by 30 years after forest conversion, the cocoa agroforestry system had re-accumulated up to 38.8 Mg C ha^{-1} or 85% of initial forest carbon stock values. This is in accordance with Monroe et al. (2016) who highlighted that systems of age 20 years and more (‘cabruca’ cacao, *Erythrina* cacao, and rubber system) did not differ significantly from the natural forest in overall SOC stock (i.e. up to 1 m soil depth). Contrarily, conversion of natural forest to full-sun cocoa plantations leads to severe soil degradation and the decline in SOC, N and CEC (Tondoh et al. 2015).

7.2 Litter and Humus Quantity and Quality

Litterfall and humus quantity is a function of tree presence in the field. Dawoe et al. (2014) indicate the amount of litterfall (Mg ha^{-1}year^{-1}) along the land-use conversion as follows: forest 8.8, 3-year-old cocoa 5.0, 15-year-old cocoa 8.2 and 30-year-old cocoa 10.4. One can see the decline in early years and recovery approx. by the 15 years after establishment. Thirty years after establishment, the annual litterfall exceeded the original values of natural forest. Similarly, the same trends are obvious for stand litterstock (Mg ha^{-1}year^{-1}), 4.56, 3.57, 5.78 and 5.89, respectively. Another study (Dawoe et al. 2010) on litterfall implied significant differences in quality between litter from forest and litter from cocoa plantations. The first had higher concentrations of nitrogen and lower concentrations of soluble polyphenols and lignin compared to the latter. They also confirmed the hypothesis that the decomposition decreases following forest conversion to shaded cocoa systems and that N-including ratios are good indicators of litter quality and decomposition rate.

However, there are probably high degrees of dissimilarities among cocoa AFS types as implies the study of Fontes et al. (2014). According to them, the cocoa-*Erythrina* systems present a higher capacity to recycle nutrients compared to the cocoa cabruca systems. The mean annual litter production ranged from 4.6 to 8.5 Mg ha^{-1}.

7.3 Physical Soil Properties

Dawoe et al. (2014) studied soil properties under the land-use conversion from primary forests to cocoa agroforestry (forest, cocoa AF 3 years old, cocoa AF 14 years old and cocoa AF 30 years old). They found out no significant differences in sand, silt and clay distributions in topsoil (0-10 cm depth). In the 10–20 cm depth, they stated decline in clay particles the third year after cocoa AF were established. However, clay content reached the original values with time. On contrary, Owusu-Sekyere et al. (2006) found a positive change in sand and silt and negative change for clay in reference to baseline (primary forest). Generally, soil texture can be considered as unaffected by land-use transition mentioned above. Bulk density can be temporarily significantly higher in topsoil due to decrease in soil organic carbon. However, it returns to its original level. The deeper soil horizons remain untouched in this respect (Dawoe et al. 2014). In opposite to that, Tondoh et al. (2015) showed significantly higher bulk density in full-sun systems along the chronosequence – during conversion from natural forest 1.23 ± 0.05 (forests) to 1.42 ± 0.04 (20-year-old cocoa plantations).

Similar trends can be expected for soil porosity: decreasing in topsoil (even in long term) while remaining relatively stable in deeper soil layers (Dawoe et al. 2014). However, this porosity does not reflect aeration in soils due to rooting of trees in deeper soil horizons building a system of cracks affecting positively the water infiltration and eliminating surface run-off.

7.4 Soil Erosion, Water Regime and Availability

Soil erosion jeopardizes sustainable development and delivery of ecosystem services notably in the tropics, where the high rainfalls occur. After Labrière et al. (2015), the implementation of sound practices of soil and vegetation management (e.g. no-till agriculture) can reduce erosion by up to 99%. There are tens of comprehensive studies worldwide (thousands of measurements) that have been conducted till now in this respect according to recent review of Labrière et al. (2015) and older works, e.g. Lal (1989). Some of them encompass agroforestry systems in general into their experimental design. Nevertheless, researches dealing exactly with soil erosion in cocoa agrosystems are relatively scarce.

Young (1990) states that combinations of several plantation crops, such as coconut with cacao and/or coffee, possibly with interplanted vegetables can be stable on slopes of up to 40%.

Hashim et al. (1995 in Poudel et al. 2000) reported about 11 times more soil loss from a bare plot compared to a plot planted with cocoa in Malaysia.

Sidle et al. (2006) cite also Hashim's study (Hashim et al. 1995) comparing annual run-offs per ha (Mg $ha^{-1}year^{-1}$) of several types of cocoa agroforestry: cocoa and shade trees plus (i) intercropped with banana + bare ground, 70; (ii) intercropped with banana + legume ground cover, 3.4; (iii) monocropping + bare ground, 11.2; (iv) monocropping + legume ground, 1.0; and (v) bare soils, no crops, 121 $t.ha^{-1}.year.^{-1}$. The pure cocoa and shade trees even with bare ground imply more than ten times less soil run-off than in the case of a bare soil. The monocropping (cocoa + shade trees) with legume ground (120 times less run-off in comparison with bare soil, respectively) appears the best combination in this respect. This study clearly shows how important the vegetation cover plays its role as an efficient measure against soil erosion.

Hartemink (2005) states in his review that most annual crops provide adequate cover within 30–45 days after planting and pastures within 2–6 months and tree crops require 2–5 years to close their canopy. Naturally, the erosion is greater in the initial stages after forest cuttings before a new tree canopy develops. Therefore, they recommend to use and manage cover crops, such as cacao ‘cabruca’ systems, where cacao is planted in partially cleared forestland where some large trees were retained.

Cocoa AF systems are advantageous for combating soil erosion in several respects: (i) the cocoa and shade trees slow down the speed of through falls during storms and thereby spread the water amount coming to the ground within a longer period, reducing water erosive effect; (ii) in mixed stands, the shade trees are usually rooted in deeper horizons (up to 2 m) than cocoa that mostly occupy topsoil [0–20 cm is considered as active lateral root zone according to Kummerow et al. (1982) in Isaac et al. 2007; Lehmann 2003 states the depth of 75% root activity to be 10.2 cm]. Thereby, trees build a system of cracks along their roots, through which the rainwater can faster infiltrate downwards to the ground waters. It results in decreasing of water mass moving on the surface and having a potential for soil runoff (creating erosion pathways). Furthermore, according to Isaac et al. (2014), root modification in the presence of secondary species may under certain conditions (sandy soils) limit competition for water due to differentiation of belowground allocation and resource acquisition zones. On the other hand, the shading canopy can play a positive role also during dry season by reducing the evapotranspiration. Therefore, AF systems can mitigate the adverse effects of both climatic extremes.

7.5 Biological Soil Properties

Microbial activity is related to organic matter, its quantity and quality. The longitudinal study of Dawoe et al. (2014) confirms this affirmation, and its results showed that temporal changes in soil microbial biomass were closely correlated to changes in SOC and total N. All these parameters decreased immediately after forest conversion (3 years), thereafter increasing with plantation age. Alfaro-Flores et al. (2015) stated that soils from fallow plots and soils under agroforestry had higher microbial biomass than soil under monocultures, most likely because of fresh organic matter input on microbial biomass. Indeed, the microbial quotient showed a significantly higher value in soils under conventional agroforestry than in soils under organic monoculture in dry season. This implies that besides the input of OM, mineral fertilization may play a role on the fraction of available carbon. Utomo et al. (2016) found in Indonesia that multistrata cocoa-coconut agroforests had highest organic carbon and soil organic matter, conditions supporting the growth and activity of beneficial soil microbe groups (*Pseudomonas* spp. and *Trichoderma* spp.) compared with cocoa monocultures and simple cocoa-rubber agroforests. Most probably, the casual relations between soil microbes and SOM are mutual, although soil organisms are known to show certain redundancy among functional species groups, and thus the loss of species or changes in composition may not affect decomposition rates (Tscharntke et al. 2005).

Snoeck et al. (2009) stated that vascular arbuscular mycorrhizal (VAM) spore density was significantly lower in the young cocoa agroforests (16 spores g^{-1} dry soil) than in the old cocoa agroforests (36 spores g^{-1} dry soil), while levels in the nearby secondary forest (46 spores g^{-1} dry soil) were not significantly different from old cocoa. However, the spore density was significantly highest in the short fallow (98 spores g^{-1} dry soil).

Concerning soil macrofauna, with land-use transition from forests to full-sun cocoa plantations, abundance and species richness may increase due to the appearance of species adapted to degraded lands while some other native species disappear, as Tondoh et al. (2015) showed on the example of earthworms. After Rousseau et al. (2012), the most crucial abiotic factors affecting the abundances of selected macrofauna groups were correlated with four well-accepted abiotic soil quality indicators (bulk density, sum of bases, pH and carbon). This is in good agreement with findings of Moco et al. (2010) from Bahia region (Brazil) that attributes affecting soil fauna in cacao agroforestry systems are mainly pH and bulk density in soil and also polyphenols and lignin content in the litter. The faunal communities were more sensitive to litter quality than soil quality. Therefore, litter management could be a good practice to maintain healthy activities of the faunal community and to maintain improved ecosystem functioning in cocoa agroforests.

A total of 192 ant species from four strata were found by Delabie et al. (2007) in extensive sampling of a cocoa plantation with a relatively simple shade canopy (comprised primarily of *Erythrina*). Species richness in the cocoa plantations corresponded roughly to that of low-diversity native forests, and species composition of cocoa plantations was mostly like native habitats (forest and mangroves), while ant composition in other agricultural habitats was mostly similar to that of urban areas. They highlight traditional multistrata AFS such as cabruca plantations to be providing important habitat for ants generally and for ant species of conservation concern.

Although cocoa agroforests cannot substitute natural primary forests, they are invaluable to conserve ecosystem services, especially in tropical agricultural dominated landscapes. From the soil management perspective, they play an important and irreplaceable role in maintaining soil fertility by litterfall inputs and in soil protection against erosion, as well as conserving an important part of soil biodiversity. They might be a significant sink of both above-ground and belowground carbon. Cocoa together with shade trees mitigate adverse climatic effects, e.g. evaporation, and help maintain water availability in dry period.

8 Economic Benefits of Cocoa Agroforests

Cocoa is among the most demanded crops worldwide with expectations of doubling the demand for its products by 2050 (Bisseleua et al. 2009). Nevertheless, price fluctuations at global markets may lead to the abandonment of cocoa (Ruf 1995).

Smallholders are core stakeholders in cocoa development initiative as they currently produce more than 90% of its production worldwide and they are better able to cope with slumps in world price than large-scale plantations (Ruf 1995; Panlibuton and Meyer 2004). Traditionally, cocoa trees have been planting in diversified farming systems supporting environmental sustainability and bringing economic benefits to out-growers as well. However, economy is always bound with markets, consumer behaviour and agricultural policy. Despite limited number of studies on economic aspects of cocoa agroforestry, certain trends are clear. Firstly, no clear relationship was observed so far between agrobiodiversity and economic success. Secondly, cocoa planting is always connected to tropical rainforest degradation. Nevertheless, from this point of view, it is important that at farm management level, there are positive economic benefits from cocoa agroforests in different ecosystems, e.g. from tropical forest areas or savannah, which give a sound background for decision-making process to focus also our attention towards other regions (Bisseleua et al. 2009; Ruf and Schroth 2015). Thirdly, it is obvious that the overall extensiveness of the system represents the limiting factor of productivity in highly biodiverse agroforestry systems compared to the highly intensified plantations. However, several studies from different regions are showing that systems with higher (agro)biodiversity are economically competitive with monocultures, such in the case of Cameroon or Indonesia, and the value of resources, particularly land, is higher as well (Duguma et al. 2001; Clough et al. 2011; Utomo et al. 2016).

Considering the limiting factor of highly diverse agroforestry systems, it is often considered that the productivity of the main crop is lower due to extensiveness of the system, when the productivity is compared to the highly intensified plantations. Yet, recent research has counteracted that notion. Clough et al. (2011) showed that species richness of trees, fungi, invertebrates and vertebrates did not decrease with high yield of cocoa in Indonesia. Authors proofed that high natural biodiversity is compatible with high yielding system (but modest shade intensity must be kept).

Study from Cameroon illustrates that cocoa agroforests were profitable under various scenarios, even when products of shade trees were not included in the analysis (Duguma et al. 2001); however, the role of fruit tree production in such agroforests is very important for their economic sustainability and stability.

Comparing the cocoa yields in Alto Beni, the results showed significantly higher cocoa dry bean yields in monoculture (+150%) and significantly lower yields in the agroforests (−70%), the third year of harvest; however, if comparing total system yields (together with other annual and perennial crops), various agroforests yielded much higher (+80–160%) compared to monocultures (Andres et al. 2016). Short-term profitability of agroforests was lower mainly because of the initial investment to install the systems and due to higher labour costs. In longer term, net returns from cocoa agroforests were higher compared to the monocultures.

Comparing total land equivalent ratio complex in Indonesia, the cocoa-coconut agroforests had the highest value (1.36) comparing with cocoa monocultures and cocoa-rubber agroforests, indicating highest yield advantages for those complex agroforests (Utomo et al. 2016).

From the economic point of view, such findings must be however understood on the long-term basis as benefits from higher yields in agroforestry system are reached only after a certain period. While there is ample evidence for the high ecological and social potential of cocoa agroforests (Clough et al. 2009; Tscharntke et al. 2011; Jacobi et al. 2014), recent literature suggests that under current market conditions they are often not economically viable in the short term compared to monocultures (Vaast and Somarriba 2014; Andres et al. 2016). This is mainly because of the relatively high initial investment needed to develop sound farming systems and due to the higher labour costs (Lojka et al. 2008; Andres et al. 2016).

Last, but not least, economic incentives and traceable value chains may improve both economic situations of out-growers, to meet expectations of the consumers regarding the quality and quantity of the products and to keep biodiversity and economy in balance. Ecological benefits represent good potential for selling final production from cocoa agroforest at a much higher price. These economic and social challenges are suitable for diverse and small-scale farming systems (Clough et al. 2009; Tscharntke et al. 2011; Jacobi et al. 2014). Although certification schemes bear numerous trade-offs, Jacobi et al. (2015) documented that Bolivian farmers with organic certification received even 42% higher prices for their cocoa than conventional farmers in the region, partly due to organic and Fairtrade premiums. This represents a huge potential to make agroforestry cocoa systems more economically competitive under current market conditions (Vaast and Somarriba 2014; Jacobi et al. 2015).

It should be noted that in commercially oriented cocoa agroforests, the farmers tend to prefer lower diversity and the whole system simplified down to the economic keystone species. On the other hand, cocoa is being commonly commercialized even from the highly diverse systems, and research is showing that economic analysis should consider the whole production system as farmers often derive their income not solely from cocoa crop but from a diverse portfolio of species (Cerda et al. 2014; Andres et al. 2016). This holistic perspective is indeed often overlooked or not considered by the governmental policies or cocoa-oriented researches.

Full-sun systems can achieve high yields in short term; however cocoa production will decline within less than two decades, and monocultures thus must be completely renewed much earlier than shaded systems. Moreover, these systems also do require continuous input of costly agrochemicals and constant management to attain their maximum yield potential (Beer 1987; Andres et al. 2016).

9 Discussion and Recommendations

As the current cultivation of cocoa brings lots of challenges, based on extensive review of the current literature, we tried to collect and analyse all strengths and opportunities of cocoa agroforests on one hand but also looking on weaknesses and threats on the other hand (see Table 23.3, presenting SWOT analysis). It is possible to predict that the demand for chocolate and other cocoa products will increase in

Table 23.3 SWOT analysis matrix for evaluation of cocoa agroforests

	Favourable/helpful	Unfavourable/harmful
	Strengths	*Weaknesses*
Internal	Robust and sustainable land-use system with increased land value	Lower cocoa bean yields
	Long-term production	Higher labour input
	Natural environment for cocoa trees	More complicated management – new skills needed
	Some pest and disease suppression (e.g. witches' broom)	Limited options for mechanization
	Lower need of external agricultural inputs (fertilizers and pesticides)	Some pest and diseases increase
	Conservation of biodiversity	Access to planting material for diversification might be limited
	Maintenance of soil fertility	Difficult marketing of high diversity of products
	Higher socioecological resilience	Lack of price premium for agroforestry cocoa
	Diversification of farm products – food and income	Cause of tropical deforestation
	Opportunities	*Threats*
External	Provision of ecosystem services at the global level	Push for intensification of production leading to shade tree removal
	Suitable tool for regional biodiversity conservation	Elimination of shade trees in later years leading to bust
	High cocoa germplasm diversity available	Change of agroforests to full-sun monocultures
	Higher carbon sequestration and climate change adaptation	Boom-and-bust cycle
	Reduced ecological footprint by decreased use of agri-inputs	Intensification of cocoa agroforestry needs know-how transfer
	Opportunity for integrated pest and disease management	Lack of management guidelines for management of shade trees and cocoa pruning
	Growing demand for environmentally friendly cocoa	Lack of multidisciplinary and participatory research and development taking farmers' perspective into account
	Premium pricing and certification	Lack of agroforestry recognition by governmental policies
		No holistic view at the whole system and its products among cocoa stakeholders

the coming years, and this scenario poses a challenge of how to make that increase of production sustainable. Up to now, the rise in production has been achieved largely by the extension of cultivated area, not by the increase of the yields. However, the historical experiences of boom-and-bust of cocoa production have shown that intensification of production usually connected with reduction of shade trees. The intensive use of agrochemicals is able to improve yields only in the short term and usually leads to a total collapse of the cocoa industry in growing regions. Moreover, the fact that cocoa is usually grown by small farmers and their ability to continuously employ high inputs in agrochemicals is usually very limited. Short-term yield gains through shade removal reduce the long-term resistance and resilience of the system, due to unmanageable pest pressure, vulnerability to changing climate and difficulties to rejuvenate cocoa (Steffan-Dewenter et al. 2007). However, there is still rather limited evidence in the literature that cocoa agroforests could substantially decrease the pressure of pest and diseases.

On the other hand, we cannot simply allow that the increase of production is achieved on the expense of the remaining tropical forests as it usually happened up to now. There is still a growing threat that the demand for chocolate could be a cause of increased deforestation of very precious humid tropical forest, usually appreciated for exceptionally high biodiversity. The shifting of cocoa production fronts is undeniably the largest environmental problem associated with the cocoa sector, and until now, the commitments to sustainability by the cocoa-growing sector have not been successful (Clough et al. 2009). First and foremost, we must sustainably intensify existing cocoa farming systems particularly through timely and sound agricultural management. Afterwards, we should find sustainable strategies to establish cocoa agroforests on already deforested lands and secondary forests. An important decision faced by cocoa farmers is whether to replant existing areas or clear new areas for planting. There is often little incentive for farmers to replant in existing fields when there is forest available for clearing, due to issues of productivity and labour requirements (Franzen and Mulder 2007). There is an urgent need to find methods and incentives that would prevent farmers from clearing primary forest and rather renew their existing plantations or reforesting non-forested land with cocoa agroforests.

Huge potential for cocoa growing rests in its nature to thrive under the shade of trees. The environmental value of shade trees is provided by their forest-like structure and functions (Perfecto et al. 2007). Moreover, the trees that farmers usually use in their cocoa plots also have social, economic value and can help in reducing the vulnerability of households to climatic stress, pest outbreaks, falling prices and food insecurity. Reaping the long-term advantages of shaded cocoa agroforestry does not exclude intermediate levels of agroforestry intensification: reducing canopy cover from 80 to 40% can double the income of local farmers with only minor changes in biodiversity and associated ecosystem services (Steffan-Dewenter et al. 2007). Nevertheless, the challenge is that once farmers fully convert the system down to monoculture, they tend to develop negative perception about shade trees and diversity (Clough et al. 2009; Ruf 2011). We may assume that in the case of monoculture production collapse, farmers will not restore their plots, but they will enter a forest to obtain new land (Ruf 1995). Alternatively, famers may switch completely to a different commodity such as oil palm/rubber plantations or annual food crops (Clough et al. 2009). Researchers and extension services have to find good management strategies for cocoa growing that fits to the abilities, capacities and expectations of small farmers. Finding strategies for growing cocoa in long-term producing low external input agroforests should be the goal.

Halting cocoa boom and bust cycles may require involvement before the problem occurs, ideally in the early stages of cocoa booms to prevent initial mismanagement (Clough et al. 2009). The rapid cocoa-bust phase has been linked to the shade removal (Arshad et al. 2015) but also to the inability of farmers to cope with increasing pressure from pest and diseases and incapacity so far of researchers to provide them with resistant cocoa material (P. Vaast pers. communication). Instead of removing shade trees at the aging phase when cocoa yield starts to stagnate due to pest and disease problems, adequate cocoa tree management (pruning and timely rejuvenation of the planting material) as well as shade trees (pruning and thinning) should be ensured. The origin and nature of the shade-loving cocoa should be respected, particularly as demonstrated on short viability and low vitality of trees grown in monocultures.

Current research clearly shows the sore need of incorporating more genetically diverse planting material into cocoa plantations and seed gardens, especially in terms of germplasm showing resistance to hosts of diseases and pests, because it would substantially contribute to the sustainability of cocoa production and the boom-and-bust cycle could be avoided. The improved material already existing in germplasm banks, breeders' collections and seed gardens should be made more available to farmers, e.g. through organizing field days, developing nurseries and other measures. Nevertheless, the genetic base of the germplasm available in breeders' collections is also narrow (Zhang and Motilal 2016). An essential tool to increase the low functional genetic diversity in cocoa-producing countries is long-term germplasm improvement by pre-breeding, i.e. introgressive hybridization of exotic germplasm, which allows accumulation of resistance genes/alleles (Iwaro et al. 2000; Zhang and Motilal 2016). Lanaud et al. (2009) performed a quantitative trait locus analysis and concluded that there are several sources of disease resistance, which could be cumulated in the same variety to improve the resistance in cocoa, but improved resistant material ready to be mass released to farmers does not exist so far (P. Vaast personal communication). New breeding strategies are therefore needed to combine more disease resistance genes from the so far unexplored wild germplasm and provide farmers with enhanced genetic diversity. There is a need to reorient the breeding program from the focus on high-yielding varieties to the development of disease-resistant and shade-tolerant varieties (Duguma et al. 2001). With increasing interest for the high-quality chocolate, also breeding for a fine cocoa flavour we see as a future option particularly for cocoa grown in agroforestry systems.

Growing cocoa in agroforest usually lowers the need for expensive external inputs such as agrochemicals. However, labour intensity remains a big challenge (Andres et al. 2016). It is known that appropriate fertilization might increase yields significantly; however, Van Vliet et al. (2015) identified and discussed three main knowledge gaps of increasing cocoa yield by fertilizing: a better understanding of cocoa tree physiology, effects of shade management and methods to determine nutrient deficiencies for adequate fertilizer recommendation.

The functional role of agrobiodiversity in the system should be valued and explored further. Innovative practices have to be developed, particularly with respect to shade regulation (Vaast and Somarriba 2014). This includes initiating selection programs for cocoa genotypes in the context of agroforestry management, as well as appropriate practices of spacing and pruning trees at critical times of the production cycle (Andres et al. 2016).

Considering recent findings related to trade-offs between biodiversity and productivity, Clough et al. (2011) showed that species richness of trees, fungi, invertebrates and vertebrates did not decrease with high yield of cocoa in Indonesia. In the same country, Utomo et al. (2016) found that cocoa-coconut agroforestry is the most environmentally friendly and most productive cocoa production system, compared to other systems including cocoa monoculture. The latter studies show that high natural biodiversity is compatible with high cocoa yield. In Bolivia, research is showing that cocoa in agroforests is reaching lower yields compared to monocultures; nevertheless, cocoa agroforestry outperforms financially when all products of the system are considered (Schneider et al. 2016; Andres et al. 2016).

There is a need to find economic incentives for maintaining shade in cocoa production. Paying cocoa farmers to maintain and diversify their shade trees, through premium producer prices and, in the future, remuneration for carbon storage in shaded agroforests, constitutes an interesting solution for a part of the growing area (Clough et al. 2009). Farmers should get access to credits and extension services under the condition of establishing cocoa in agroforestry scheme not in full-sun scheme. Certification standards also hold a certain potential to influence the future design of the cocoa production systems (Andres et al. 2016). In Ecuador, chocolate manufacturers, consumers and environmentalists encouraged farmers to maintain shade canopies by paying a premium for the traditional, shade-loving, high-quality aromatic cocoa varieties (Bentley et al. 2004).

Other potential rests in the production and marketing of the shade tree products that can offset the increased labour demands and increase profitability. In Central American countries, Cerda et al. (2014) found that contribution of diverse array of agroforestry products to family benefits is similar or even higher than that of cocoa. In some cases, agroforestry products might be as important as the main crop for the small-scale farmers. The farmers should be encouraged to maintain and plant the local native tree species that are compatible with their environment, they usually know their management and they can provide them with valuable products. In more commercially oriented multistrata systems, it will be a matter of research to help farmers to identify the appropriate species, improve their productivity and find out the optimal tree density. Generally, as farmers have usually developed own cultural preferences for trees and are also involved in the local economy, the role of researchers and extensionists will be foremost to reflect those cultural preferences (bottom-up approach) and to recommend trees important from an (agro-)ecological perspective (such as legumes and ecologically important species). Focusing on farm diversification may be the most effective way of optimizing ecological, economic and social outcomes (Franzen and Mulder 2007).

On the national and international level, cocoa agroforestry should be viewed and supported as an important biodiversity conservation tool. While they cannot replace primary forests in terms of biodiversity, it is also evident that under certain conditions they can play a valuable ecological role in human-dominated landscapes (Asare 2006). Understanding the complexity of agroforestry systems and valuation of the agrobiodiversity within them, as well as designing new agroforestry systems, will require holistic lens valuating whole diversity, ideally with participatory approaches involving farmers' knowledge and perspective in the research (Jagoret et al. 2014; van der Wolf et al. 2016). The potential of these agroforests in their ability to sequester carbon should also be thoroughly investigated, particularly in the face of changing climate.

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Chapter 24
Evolution of *Acacia koa* on the Hawaiian Islands

K. L. Ishihara, M. Corpuz, C. W. Morden, and D. Borthakur

Abstract *Acacia koa* (koa), a leguminous timber wood tree, has a significant importance in the economy, ecology, and culture of Hawaiʻi. Natural *A. koa* forests have been gradually disappearing over 100 years due to ranching and an infestation by the *Fusarium* wilt disease. Recently, there has been a growing interest for reestablishment of *A. koa* in Hawaiʻi to create more profitable, ecologically sound, sustainable land-use systems. For successful development of agroforestry areas with wilt-free and high wood-quality *A.* koa trees, it is important to have a better understanding and awareness of the nature of the plant. This report presents a review of the current knowledge on *A. koa*, including its roles as an agroforestry tree, botanical characteristics, genetic diversities, propagation methods, and evolution.

Keywords *Acacia koa* · Agroforestry · Tree legume · Timber · *Bradyrhizobium* · Canopy nodules

1 *Acacia koa*: An Agroforestry Tree

Acacia koa A. Gray (koa; Fig. 24.1), the largest native tree of the Hawaiian Islands, is a member of the legume family (Fabaceae) and the mimosa subfamily (Mimosoideae). Some consider Mimosaceae as a separate family. The native *A. koa* forests are broadly distributed across all six major Hawaiian Islands, Hawaiʻi, Molokaʻi, Maui, Lānaʻi, Oʻahu, and Kauaʻi (Wagner et al. 1999). It can grow to a height of up to 35 m (Elevitch et al. 2006). *Acacia koa* serves as a vital resource for the Hawaiian Islands, providing benefits ecologically, culturally, and economically.

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Fig. 24.1 *Acacia koa* trees, courtesy of Dan Adamski

First, as a nitrogen-fixing legume, *A. koa* plays an important role in enhancing soil fertilities of forests. Many native plant species are associated with *A. koa. Metrosideros polymorpha* (‘ōhi‘alehua) is one of the most important trees in Hawaiian forests along with *A. koa*. Other important understorey trees include *naio* (*Myoporum sandwicense*), *‘ōlapa* (*Cheirodendron trigynum*), *kāwa‘u* (*Ilex anomala*), *kōlea* (*Myrsine lessertiana*), *kōpiko* (*Psychotria* spp.), *‘iliahi* (*Santalum* spp., sandalwood), *olopua* (*Nestegis sandwicensis*), and *pilo* (*Coprosma* spp.) (Mueller-Dombois and Fosberg 1998; Wagner et al. 1999; Elevitch et al. 2006; Baker et al. 2009). *Acacia koa* also provides habitats for many native fauna and flora, including the endangered Hawaiian honeycreepers, such as *‘akiapōlā‘au* (*Hemignathus munroi*) and *‘ākepa* (*Loxops coccinea*) (Sakai 1988; Whitesell 1990; Elevitch et al. 2006; Baker et al. 2009). Secondly, *A. koa* is culturally very important. “*Koa*” means bravery or warrior in Hawaiian, and it provides a valuable wood to native Hawaiians. It was traditionally associated with royalty and was used to make outrigger canoes for fishing, racing, and voyaging along with canoe paddles, spears, and, more recently, surfboards and ukuleles (Abbott 1992; Krauss 1993; Elevitch et al. 2006; Baker et al. 2009). The beautiful texture, hardiness, and carving quality of *A. koa* timber, also referred to as Hawaiian mahogany, additionally make it a highly priced commodity with a current market value of up to $125 per board foot (Baker et al. 2009). The wood color, varying from blond to dark red, and the grain figures, ranging from plain to curly (highly figured), are the most important determinants of the price; curly wood with a dark red color is the most highly valued (Baker et al. 2009). The wood is used for fine furniture, decorative items, musical instruments, and jewelry. The gross value of *A. koa* timber and the wood products produced is estimated to be in the range of \$20–\$30 million annually (Yanagida et al. 2004; Baker et al. 2009).

Over the past century, cattle ranching, grazing by wild animals, agriculture and land developments, and invasive plant species have severely reduced *A. koa* forests (Whitesell 1990; Ewel and Bigelow 1996). However, in recent years, the importance of *A. koa* has been recognized, and there has been a growing interest in the reestablishment of the tree to create more profitable, ecologically sound, sustainable land-use systems (Newell and Buck 1996; Mitchell et al. 2005; Perkins et al. 2014). For example, many agencies, such as the United States Fish and Wildlife Service (USFWS), the Hawai‘i Division of Forestry and Wildlife (DOFAW), and the National Park Service (NPS), have begun growing *A. koa* in mesic montane forests and parklands in the island of Hawai‘i to protect forest birds, such as *‘akiapōlā‘au* and ‘*ākepa*, as well as to develop sustainable *A. koa* forestry that will help landowners to maintain economic value of their lands.

2 Botanical Characteristics of *A. koa*

Acacia koa is a fast-growing tree, growing at the rate of ~1.5 m in height per year for the first 5 years under favorable conditions (Elevitch et al. 2006). It typically reaches heights of 15–25 m with a canopy spread of >6 m, but some populations have a smaller and shrubbier form (Elevitch et al. 2006; Baker et al. 2009). It is found in a broad range of habitats and grows at elevations from near sea level to 2000 m, in mesic or wet forests with annual rainfall from 1850 to 5000 mm (Harrington et al. 1995; Anderson et al. 2002; Wilkinson and Elevitch 2003; Baker et al. 2009).

Acacia koa produces two types of leaves during its life cycle; young trees have bipinnate compound leaves with 12–24 pairs of leaflets as true leaves (Fig. 24.2a), whereas mature plants produce phyllodes that are sickle-shaped pseudo-leaves derived from the flattened petioles (Fig. 24.2b). The flowers of *A. koa* are pale yellow spherical heads about 8–10 mm in diameter arranged in axillary racemes (Fig. 24.3). The flowers bloom year-round, with peaks in mid- to late winter and early summer (Whitesell 1990) starting from when the trees are 2–3 years old (Allen 2002). The flowers are hermaphroditic (bisexual) and have numerous long, curled stamens, corollas, and a single style (Whitesell 1990; Wagner et al. 1999). They are dichogamous, with anthers releasing pollens 3–8 days before the stigma reaches maturity. This arrangement is favorable for cross-pollination among flower heads on different trees and also on the same trees (Elevitch et al. 2006; Baker et al. 2009). Because its flowers provide good quantities of nectar, *A. koa* is pollinated by various insects, such as honeybees (*Apis mellifera*), allowing long-distance dispersal of pollen (Lamoureux 1971; Sakai et al. 1995; Elevitch et al. 2006). Three to four months following pollination, *A. koa* produces flattened, oblong pods with the length of 8–30 cm and the width of 0.8–2.5 cm (Wagner et al. 1999; Baker et al. 2009). Each pod contains 6–12 seeds arranged in either transversely, longitudinally, or at an

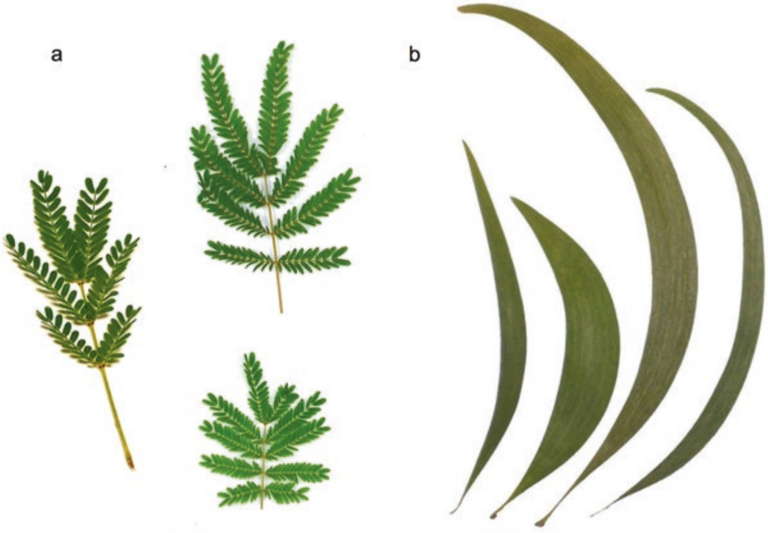

Fig. 24.2 Different leaf forms of *Acacia koa*: (**a**) bipinnate compound true leaves and (**b**) phyllodes

Fig. 24.3 Flowers of *Acacia koa*, arranged in axillary racemes

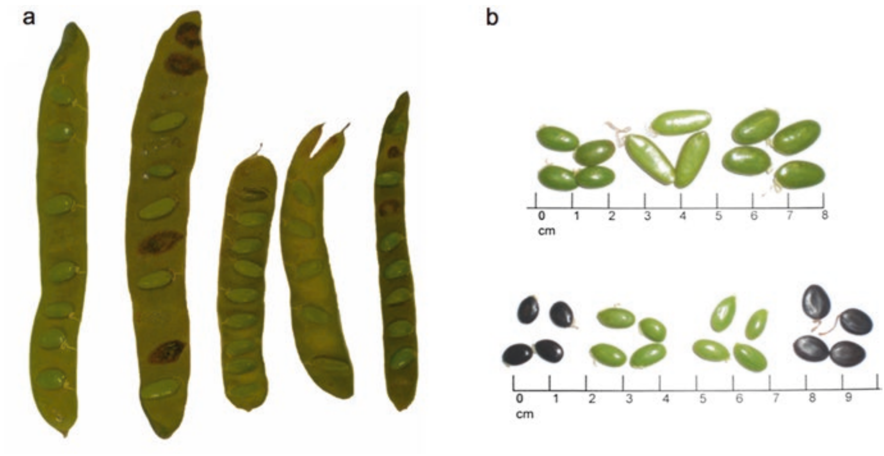

Fig. 24.4 Different morphological varieties of (**a**) seed pods and (**b**) seeds from different populations of *Acacia koa*

angle in the pods, depending on *A. koa* types (Fig. 24.4a). The seeds are laterally flattened ellipsoid, 6–13 mm long and 3–9 mm wide, dark brown to black in color, and slightly shiny (Fig. 24.4b; Whitesell 1990; Sun et al. 1997; Wagner et al. 1999). *Acacia koa* forms a strong lateral root system besides having a large taproot; some of its shallow lateral roots may be partially exposed at the soil surface (Elevitch et al. 2006). As a legume species, *A. koa* forms root nodules, which are occupied by the symbiotic nitrogen-fixing bradyrhizobia; interestingly, nodules are also found in the adventitious roots established within the canopy of *A. koa* (Leary et al. 2004). Leary et al. (2004) also observed numerous nodules formed by fine hairy roots that emerged from the ground under layer of decomposing leaf litter in the forest floor.

3 Wilt and Dieback Diseases of *A. koa*

Acacia koa forests have been suffering from a devastating vascular wilt and dieback disease caused by a fungal pathogen *Fusarium oxysporum* f. sp. *koae*. It is the major cause of decline of *A. koa* in the native Hawaiian forests in recent years, and despite the growing interest in *A. koa* forests, restoration attempts are hampered due to this pathogen (Gardner 1980, 1996; Anderson and Gardner 1998; Anderson et al. 2002; James 2005; Pejchar and Press 2006; Dudley et al. 2007). *Fusarium oxysporum* is a soilborne fungus that typically infects the host plants through the root system (MacHardy and Beckman 1981). Upon entering the roots, mycelium advances intercellularly to the plant's xylem vessels, where it is then able to spread upward leading to clogging of vessels due to the accumulation of mycelium and formation of host plant defense, such as formation of tyloses and gum (Pietro et al. 2003). Once too many xylem vessels are clogged, the host dies due to the disruption of water movement (MacHardy and Beckman 1981). *Fusarium oxysporum* can also survive an extended period in the soil without its hosts, so it is difficult to control this ubiquitous and hardy pathogen.

Efforts have been made to breed *A. koa* for wilt resistance by selecting resistant families of *koa* in field trials. In *A. koa* improvement program, half-sib progenies grown from the seeds obtained from a single mother tree are considered a family. In the trials performed by Shi and Brewbaker (2004), the seedlings were exposed to naturally occurring levels of *F. oxysporum* infection to determine the long-term survival rates. James (2005) and Dudley et al. (2007) isolated virulent strains of *F. oxysporum* f. sp. *koae* that have been used to artificially inoculate the seedlings for 100-day greenhouse trials to determine the survival rate and select resistant families (Dudley et al. 2015). Field trials are currently being conducted to validate the results of the greenhouse trials. These results may be used to confirm if this screening method can be used to select resistant *A. koa* families prior to outplanting (Dudley et al. 2015). However, this process is both time-consuming and cost-ineffective because it can take up to several years (Rushanaedy et al. 2012). For more rapid selection, molecular approaches are also being developed to select for disease resistance. Rushanaedy et al. (2012) observed that expression of chitinase genes *Akchit1a* and *Akchit1b* was higher in resistant *A. koa* families than insusceptible ones following inoculation by virulent strains of *F. oxysporum*. Chitinases are important defense enzymes that breakdown chitin in fungal cell wall infecting plants (Punja and Zhang 1993; Sharma et al. 2011), and those differentially expressed chitinases have potentials as markers for fast screening of resistant *A. koa*.

4 Propagation

Typically, *A. koa* is sexually propagated from seeds. Seeds are collected from pods that are ready to be harvested when its color changes from green to brown or black. To extract seeds, pods are dried in the sun so that they can be opened easily (Elevitch et al. 2006). Seeds have a hard, impermeable coat that requires scarification to allow water to contact the germ. In nature, friction between the seed and soil or rock substrate scarify them. Artificial scarification can be accomplished chemically by soaking in concentrated sulfuric acid for 10 min, mechanically by nicking the seed coat on the edge with nail clippers or sand paper, or a hot water treatment by soaking the seeds in near-boiling water for few minutes. The scarified seeds are planted into containers filled with well-drained potting media, in a depth of about the width of the seeds. The medium should be kept moist, and they will germinate in 2–7 days (Elevitch et al. 2006). They can be grown outdoors and no special greenhouse area is needed, but some cover is helpful for the first 2 weeks after germination to protect seedlings from hard rains (Wilkinson and Elevitch 2005). Seedlings should be inoculated with appropriate *Bradyrhizobium* strains after 1–2 weeks for enhancement of the growth (Leary et al. 2004; Elevitch et al. 2006). When seedlings reach 15–30 cm, they mature enough to be outplanted to their permanent planting site (Elevitch et al. 2006).

Due to the cross-pollinating nature of *A. koa*, the plants are highly heterozygous and heterogeneous, and it is difficult to grow a uniform population of *A. koa* trees with desired qualities. Therefore, many studies have been performed to develop a method for vegetative propagation of *A. koa* that is useful to produce genetically identical plants with superior properties, such as certain wood colors and disease resistance. Skolmen (1978, 1986) developed tissue culture techniques for vegetative propagations by air layering or rooting of cuttings under mist as well as by callus cultures derived from shoot tips. Tissue-cultured trees using this approach have been successfully outplanted. However, these methods were labor-intensive, time-consuming, and currently not suitable for large-scale propagation (Skolmen 1986). Building upon these earlier works, Nagai and Ibrahim (1997) developed a method for micro-propagation through multiplication and rooting of shoots and phyllodes of *A. koa*. Similarly, Dudley et al. (2015) used rooted cuttings as a method to propagate disease-resistant genotypes. They determined rooting efficiency of *A. koa* seedlings from various disease-resistant families and successfully outplanted the rooted shoot cuttings (Fig. 24.5). However, rooting success was still limited, and further work is necessary to optimize for higher efficiency so that it is suitable for mass propagation. Although the tissue culture methods are currently suboptimal, Nelson (2006) reported successful grafts of young *A. koa* seedlings onto rootstocks of another *A. koa* and two other acacias, *A. mangium* and *A. confusa*, for the first time. Grafts from *A. koa* plant to another and from a plant of *A. koa* to a plant of

Fig. 24.5 Outplanting of the rooted shoot cuttings of *Fusarium* wilt-resistant families of *Acacia koa* at the Maunawili Research Station of Hawai‘i Agriculture Research Center (HARC), Kailua, Hawai‘i

A. confusa had the success rate of about 70%, and the graft method of cutting and clipping two seedlings together is simple, rapid, and inexpensive (Nelson 2006). The application of this method will be especially useful to manage soilborne plant pests by joining *koa t*o disease-resistant rootstocks.

5 Ploidy Level of *A. koa*

Acacia koa is a tetraploid ($2n = 4x = 52$; Atchison 1948; Carr 1978; Conkle 1996; Hipkins 2004), and it has been proposed to be an allotetraploid based on the observation that only one pair of the chromosomes contains secondary constrictions, one indication of allotetraploidy (Shi 2003). No further research on the genome has been performed, so the genomic information of *A. koa* is currently very limited. However, the transcriptome was recently sequenced from *A. koa* seedlings through the Illumina platform (Ishihara et al. 2015). Sequencing and *de novo* assembly yielded over 85,000 unigenes, and more than half of them were annotated. Among them were complete coding sequences of many proteins, including enzymes that may be involved in wood formation and development, such as monolignol biosynthesis enzymes (Ishihara et al. 2015). A substantial number of potential SSR markers were also predicted from the transcriptome data (Ishihara et al. 2015). All the assembled sequences are publicly available on the National Center for Biotechnology Information (NCBI), and it will be a useful genetic resource for further studies of *A. koa*.

6 Genetic Diversities of *A. koa*

Acacia koa populations on the Hawaiian Islands are very diverse due to its cross-pollinating nature and diverse geographical, climatic, and topological variations within the Hawaiian Islands. The populations of *A. koa* can be grouped into three distinguishable forms, namely, "*koa*," "*koaia*," and "intermediate" types (Wagner et al. 1999; Adamski et al. 2012). The "*koa*" type forms larger trees, whereas trees of the "*koaia*" type grow only up to about 5 m in height and has a gnarled appearance. The "*koaia*" type has harder wood and grows in drier open woodlands on the islands of Hawai'i, Kaua'i, Moloka'i, Lāna'i, and Maui (Wagner et al. 1999; Elevitch et al. 2006; Adamski et al. 2012; Ishihara et al. 2016). Also, in the "*koa* type," seeds are arranged transversely in wider pods, while in the "*koaia*" type, they are arranged longitudinally in narrower pods. Another distinct characteristic is the phyllode; the "*koa* type" has broader phyllodes (1–5 cm), while the "*koaia* type" has narrower phyllodes (<1 cm; Rock 1919; Elevitch et al. 2006; Adamski et al. 2012). Because of their distinct features, the "*koa*" and "*koaia*" types have been suggested to be different subspecies or species (Adamski et al. 2012; Ishihara et al. 2016). The existence of the "intermediate" type suggests that the "*koa*" and "*koaia*" types may be subspecies rather than distinct species. The "intermediate" type, which can grow up to 10 m with its mixed characteristics of phyllodes, pods, and seeds, could be the result of the natural cross-pollination between the "*koa*" and "*koaia*" types (Adamski et al. 2012). Recently, genetic analysis on interrelationships among the three forms, the "*koa*," "k*oaia*," and intermediate type, was also conducted by Adamski et al. (2012). Using 12 microsatellite loci, genetic variation among the three types was analyzed, and the results suggested that they should be recognized as different subspecies rather than as different species, which is consistent with the morphological analysis in previous studies (Adamski et al. 2012).

Even among populations of the "*koa*" types, wide varieties in tree form, phyllode development, tolerance of rust, and other traits have been observed, and these phenotypic differences appear to be highly heritable (Sun 1996; Brewbaker 1997; Sun et al. 1997; Daehler et al. 1999). According to Brewbaker (1997), variation was greater within each island than among islands, while uniformity was generally observed within each population implying a high degree of self-fertilization. Actual genetic differences among *A. koa* populations in the Hawaiian Islands have been evaluated through an isozyme survey and a microsatellite analysis (Conkle 1996; Fredua-Agyeman et al. 2008), which interestingly presented different results. The isozyme survey showed that the expected heterozygosity of *A. koa* was 0.41, a high value compared with many other organisms, and that *A. koa* trees on the island of Hawai'i were distinct because they had unique alleles and different allele frequencies from those on O'ahu, Maui, and Kaua'i (Conkle 1996). Because *A. koa* is genetically diverse, different sampling could affect the results. Fredua-Agyeman et al. (2008) conducted a microsatellite analysis using a thorough sampling of *A. koa* trees from various populations on each island. The results showed that the populations on the islands of Hawai'i, Maui, and O'ahu were actually more closely related than from Kaua'i (Fredua-Agyeman et al. 2008).

7 Evolution

Acacia koa belongs to *Phyllodineae*, the largest subgenus of the genus *Acacia*. The subgenus *Phyllodineae* comprises 950 species out of ~1200 species in the genus *Acacia* (Mabberley 1997; Robinson and Harris 2000; Miller and Bayer 2000, 2001). The majority of the *Phyllodineae* species are found in Australia, and only 18 of the 950 species, like *A. koa*, reside outside of Australia (Brown et al. 2012). The ancestor of *Acacia koa* also originally came from Australia and is mostly closely related to *A. melanoxylon*, commonly known as the Australian blackwood (Le Roux et al. 2014). *Acacia koa* and *A. melanoxylon* have similar morphological characteristics, such as maximum height of ~35 m, and long, wide pods and phyllodes. Consistent with their morphologies, a plastid DNA analysis showed that *A. koa* has a close relationship with *A. melanoxylon* as well as *A. paradoxa*, an Australian prickly shrub (Robinson and Harris 2000). Adamski et al. (2013) also confirmed a close relationship between *A. melanoxylon* and *A. koa* in a study of genetic diversity in seven non-native *Acacia* species in the Hawaiian Islands using 31 microsatellite markers. They observed that *A. melanoxylon* had the highest percentage of amplified loci derived from *A. koa* DNA and concluded that *A. koa* of the Hawaiian Islands is most likely a descendant of *A. melanoxylon* from Australia. Despite their morphological similarities, their ploidy levels are different as *A. koa* is a tetraploid, while *A. melanoxylon* is a diploid; this polyploidy formation happened during the evolution of *A. koa* as it is a common phenomenon in many angiosperms (Masterson 1994). In plants, polyploidy is an important mechanism for adaptation (teBeest et al. 2012). A recent study showed that *A. koa* has significantly different ecological niches from *A. melanoxylon*, thriving in wider geographical ranges and environmental conditions. This wider adaptability may be due to the increase in ecological tolerance in the tetraploid *A. koa* (Le Roux et al. 2014).

Another close relative of *A. koa* is *A. heterophylla* (highland tamarind), which is an endemic species of Réunion Island, east of Madagascar (St. John 1979; Le Roux et al. 2014). *Acacia heterophylla* has narrower pods and phyllodes than *A. koa*, but they otherwise have strong morphological similarities (Le Roux et al. 2014). An ecological-niche-overlap study showed significant similarities between habitats of *A. koa* and *A. heterophylla* (Le Roux et al. 2014); both species inhabit wet to mesic forests. Recently, phylogenetic dating analyses found that *Acacia* seeds were dispersed, not from Australia, but from the Hawaiian Islands to the far away Réunion Island ≤1.4 million years ago. The analyses indicate that the establishment of *A. koa* in Hawai‘i occurred 5.1 million years ago (the age of Kaua‘i, the oldest Hawaiian Island; Le Roux et al. 2014). Furthermore, phylogenetic and genetic analyses indicate that *A. heterophylla* forms a clade nested within the variation of *A. koa*, and as such, they should be considered the same species (Le Roux et al. 2014). However, *A. heterophylla* is proposed to be an autotetraploid with the two sets of chromosomes both containing secondary constrictions (Coulaud et al. 1995), whereas *A. koa* is proposed to be an allotetraploid as described above. Since they are the same species, with one derived from the other, they must both be auto- or allotetraploids. There is a possibility that the chromosomal analysis for determining polyploidy nature of the two species was inaccurate due to limitation of the technique (Coulaud et al. 1995; Shi 2003), and further studies are needed to validate the polyploidy nature of the species.

The long-distance dispersal mechanism of acacia from Australia to the Hawaiian Islands, and then to the Réunion Island, is another question. Arrival by human assistance, birds, and free-floating seeds are the most possible dispersal strategies. Brown et al. (2012) proposed geological history and human-mediated dispersal as the main strategy of phyllodinous species of acacias including *A. koa* to move outside Australia; yet, given the preponderance of other data to the contrary, this hypothesis is not acceptable. For instance, recent research through phylogenetic dating analysis by Le Roux et al. (2014) suggested that natural long-distance dispersal is more likely rather than human-assisted dispersal since human colonization of the Hawaiian Islands occurred only in 400–600 A.D. (Olson and James 1982). Carlquist (1966) favored oceanic transfer suggesting that mature *A. koa* seed pods on tree branches may have drifted in ocean currents for prolonged periods of time. Others have suggested dispersal by seabirds (Cheke and Hume 2008; Kull and Rangan 2008). For the dispersal between the Hawaiian Islands and Réunion Island, Cheke and Hume (2008) speculated that the Hawaiian petrel strayed into the wrong ocean, finding a new similar habitat on Réunion Island. Barau's petrel, a seabird of Réunion Island, possibly came as a descendant from Hawaiian petrels; both nest at high altitudes concurrent with distribution of *A. koa* and *A. heterophylla*, respectively (Cheke and Hume 2008; VanZandt et al. 2014). Migrating petrels with *A. koa* seeds in their guts might have allowed introduction of *A. koa* into new habitats separated by vast distances (Ryan and Jackson 1987; Ryan 1988). With a hard seed coat, *A. koa* seeds can withstand intense acidity, so they may have been able to remain viable in petrel's gut for long distances of travel.

8 Conclusions

Regardless of where it came from or where it spread to, the significant importance of *A. koa* in the Hawaiian Islands remains the same. The future of *A. koa* as an agroforestry tree depends upon continuation of selection for disease resistance and wood quality and capability to provide a good source of seeds using selected trees. As mentioned above, efforts have been made to develop methods to select for disease-resistant *A. koa*; however, there are currently no definitive selection strategies for wood quality in *A. koa*. Important wood properties for selection include the grain figures and the color, both of which are influenced to a large extent by environmental factors such as geographic location (Loudat and Kanter 1996; Dudley and Yamasaki 2000). It appears that variations of the grain figure also have a genetic basis; some *A. koa* have the most valued curly grain figure systemically throughout the entire trees, while others do not (Dudley 2007). Therefore, there is a potential for genetic improvement within cultivated *A. koa* forests. The formation of the heartwood color is not well understood (Wilton et al. 2015), and the evaluation of clonal *A. koa* trees from different sites may help determine genetic and environmental factors affecting the wood color.

Following the development of successful selection strategies for these desired qualities, seed orchards should be established to provide superior seeds for planting. It is important that these orchards contain enough representation of different *A. koa* populations to establish distinctive gene pools and prevent inbreeding. Therefore, a vast area of plantation will be necessary, and it is only possible with the help of government agencies and private land owners. Currently, the Hawai‘i Agriculture Research Center (HARC) and the US Department of Agriculture (USDA) have been working to develop wilt-resistant populations of *A. koa* (Sniezko 2003). Further combined efforts of conservation agencies and landowners may lead to successful development of agroforestry areas with wilt-free, high-wood-quality *A. koa* trees that can support the ecology, economy, and culture of Hawai‘i. The tree also needs to be tested with different crops in intercropping to justify its importance as an agroforestry tree.

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Chapter 25
Microbial Biodiversity in Agroforestry Systems

K. R. Sridhar and D. J. Bagyaraj

Abstract Agroforestry system is a combination of trees with crops in the same area to have optimum beneficial ecological interactions among ecosystem components. One of the major ecosystem services of agroforestry is conservation of biodiversity in each geographic location owing to the alarming rate of destruction of forests and extent of soil perturbation worldwide. Microbial biodiversity as the hub of ecosystem facilitates sustainable agroforestry to mankind by providing food, fibre and non-timber forest products. Agroforestry system is one of the hopes for progress towards sustainable developments, ecosystem services through microbial diversity and improvement of soil health. The major candidates of importance in agroforestry include symbiotic nitrogen fixers, non-symbiotic nitrogen fixers, phosphate-mobilizing organisms (mainly mycorrhizal fungi) and disease-preventing endophytic microbes. Depending on the management and health of agroforestry, the microbial diversity boost towards tripartite or multiple associations (or consortia) with plant species, which leads to sustainable developments in favour of incalculable ecosystem services. The composition of microbial diversity could be managed based on the diversity of tree species and food crops considered for practice of agroforestry system. Global coordinated efforts in evaluation of microbial biodiversity result in greater understanding, management of agroforestry systems towards sustainability and reaping the benefit of ecosystem services.

Keywords Ecosystem service · Microbial mutualism · Mycorrhizal fungi · Nitrogen fixation · Soil health · Sustainable agriculture

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1 Introduction

The modern agricultural systems are ecologically simplified and highly demanding external input of fertilizers without scope for long-term sustainability (Altieri 1999). The deforestation of virgin forests is accelerating in alarming rate worldwide owing to expansion of modern agricultural activities leading to shrinkage of cultivable land. In addition, due to the type of management practices, agricultural soils worldwide are under threat of degradation (Araujo et al. 2012). To circumvent these problems, self-sustaining agroforestry systems (AFS) are suitable as they are genetically diverse, demand less/zero external fertilizer input, conserve/improve/regenerate biodiversity though natural input of renewable organic matter, support soil stability, prevent soil erosion/minimize nutrient leaching, serve as windbreaks/green wall and improve air-water quality. The AFS is a form of multicropping which involves combining at least one woody perennial with a crop which results in ecological and economic interactions between the two components (Palma et al. 2007). The advantages of AFS are that they compensate the loss of forest cover, support sustainable ecosystem services and derive necessary benefits (e.g. food and forest products). The term ‘agroforestry’ is referred to as land use system and technology of use of trees/woody perennials deliberately in a land where agricultural crops and/or livestock are reared (Nair 1989). The World Agroforestry Centre estimated 43% of global agricultural lands possess about 10% tree cover, while nearly 160 million hectares possesses over 50% tree cover (Zomer et al. 2009) denotes scope to revegetate agricultural land with suitable tree species.

The AFS is like traditional agriculture/farming normally practiced in developing countries from the time immemorial. The salient features of traditional farming include high degree of plant genetic diversity, which promotes biodiversity and supports interaction between plant-microbe and among microbes. It is known that such traditional polyculture cropping systems meet up to 15–20% of world’s food requirement (Altieri 1999). The traditional AFS in tropics endowed with over 100 annual and perennial plant species per field result in a variety of ecological services beyond mere production of food and shelter (Altieri 1999). Advantages are known to be high on cultivating the food crops as intercrops in AFS. Moreover, the benefits are incalculable if the AFS are properly managed to mimic vegetation architecture of natural forest ecosystems. It is known that 1 hectare of tropical rain forest is composed of over 100 tree species, and such natural yardsticks help to drive AFS in the future (Perry 1994).

The AFS is one of the viable land use propositions which results in a variety of ecosystem services and environmental benefits in a broader context such as (i) sequestration of carbon, (ii) conservation of biodiversity, (iii) enrichment of soil and (iv) improvement of air and water quality (Jose 2009). More precisely, agroforestry improves primary production, enhances pollination, supports seed dispersal, helps in pest control, prevents soil erosion, supports soil stability, increases carbon fixation, sustains biodiversity, provides clean air/water/food and projects cultural/aesthetic values (Izac 2003; Kremen 2005; Jose 2009). The AFS provide benefits in rural as well as urban landscapes (Pinho et al. 2012) by food security, household income, economic stability and thermal comfort (cooling effect) along with a variety of flowers, fruits, non-timber forest products and litter (green manure or organic matter). Besides carbon sequestration, AFS elevate organic matter and microbial diversity in soil which in turn mitigates greenhouse gas emissions.

The major components of AFS include design, management and landscape configuration (Harvey and Villalobos 2007). Design refers to composition of plant species (diverse native species), density (leads to high biodiversity) and duration (long-term rotation for stability); management refers to the manoeuvre of soil (minimal alteration), harvest (minimal or equivalent to natural disturbance) and retention of woody debris (coarse woody debris as habitat for flora, fauna and microbes); landscape configuration refers to broader issues (enhance landscape connectivity, link habitat fragments and provide corridors as buffering effect) and type of land used (degraded, abandoned and wasteland) (Harvey and Villalobos 2007; Jose 2009).

Cultivation of crops/forages as source of food/fibre needs huge quantity of nitrogenous fertilizers. As an alternative to such demand of fertilizers, if AFS are practiced especially including leguminous trees, several benefits could be derived such as pruned plant biomass as green manure, shade trees to conserve water, live supports for climbing crops and cultivation of fodder trees/grass simultaneously (see Nygren et al. 2012). In addition, AFS is beneficial in fetching fuel wood, fodder and several non-timber forest products. Consumption of 25 million tonnes of protein nitrogen per annum by six billion global population needs enormous quantity of nitrogen fertilizers (chemical and biofertilizers), if it would have to be managed only by chemical fertilizers, which will be on the cost of degradation of soil health (Desai et al. 2016).

Destruction of virgin forests means destruction of biodiversity associated with forests. Visible diversity will be mainly accounted due to loss of forest cover, but loss of invisible diversity (e.g. microbial diversity)will be at much larger scale and incalculable. The development of AFS mainly relies on its immediate surroundings, the rhizosphere and canopy/phyllosphere. Soil and canopy microbial diversity play a pivotal role in supporting and safeguarding the AFS. The microbial interaction with tree species can be beneficial, harmful or neutral. However, plant growth-promoting microorganisms in soils and plant-protecting microbes in canopy are of primary importance to mitigate AFS. As microbial diversity is the hub of AFS, its assessment, management and interactions are of immense value to compare with different types of forest ecosystems and agroforests in wide geographic area. In 2010–2020, being the biodiversity decade, the AFS is one of the hopes for boosting sustainable plant and microbial diversity. The present chapter projects the importance of microbial biodiversity in AFS with emphasis on symbiotic/non-symbiotic nitrogen fixers, mycorrhizal fungi and endophytic microbes, impact of perturbations and assessment of microbial biodiversity.

2 Diversity

AFS generally enhance organic matter accumulation in soils through the inclusion of different crops and permanent vegetation cover, which would be expected to increase the soil microbial biomass. Fallen litter and fine-root turnover may increase the soil organic matter concentration. Trees may also enhance the above- and belowground microclimate around the plant roots and may alter the soil biological properties. Earlier investigations have brought out that soil under AFS harbours greater microbial biomass compared to soils with monocrops or open grasslands (Almeida et al. 1997; Kaur et al. 2000). The diversity of microbes in agroforestry could be broadly divided into belowground and aboveground diversity. Belowground microbial diversity and their functions are dependent on the nature of AFS (e.g. composition of crop system), soil quality, rhizosphere and abiotic factors (Radhakrishnan and Varadharajan 2016). Similarly, the aboveground (e.g. canopy) microbial diversity is also influenced by the nature of tree species, phyllosphere and abiotic factors (see Sridhar 2009). Several authors have reported that soil microbial biomass and microbial diversity are greater in the AFS due to the ameliorative effects of trees and organic matter inputs and the differences in litter quality and quantity and root exudates (Mungai et al. 2005; Sørensen and Sessitsch 2007). The presence of a large and diverse soil microbial community is crucial to the productivity of any agroecosystem. The diverse microbes associated with AFS could be generally categorized as symbiotic bacteria (bacteria, *Actinobacteria* and cyanobacteria), non-symbiotic microbes (bacteria, cyanobacteria and fungi) and mutualistic fungi (arbuscular mycorrhizal fungi, ectomycorrhizal fungi and endophytic fungi). Mixtures of plant species in AFS usually allow a larger diversity and/or abundance of microbial diversity, including mycorrhizal fungi and nitrogen-fixing bacteria, than monocultures (Cardoso and Kuyper 2006; Freitas et al. 2010). Nitrogen fixation ability is known from prokaryotes as well as methanogenic archaebacteria. They have been broadly divided into symbiotic and free-living nitrogen fixers based on their ability to establish association with higher plants.

2.1 Symbiotic Nitrogen-fixing Bacteria

Although many symbiotic nitrogen-fixing bacteria are also saprophytes, some have become obligate symbionts or evolved towards high symbiotic dependence. Symbiotic association with plants mainly consists of three groups: (1) α- and *Betaproteobacteria* (nodulated plants), (2) *Actinobacteria* (*Frankiaceae*) (nodulated plants) and (3) cyanobacteria (occupy intercellular location and mucilage cavities) in bryophytes, cycads and higher plants. Nearly 60% of nitrogen supply to plants comes from biological fixation and half of that supplied by plant-bacterial symbiosis (Barea et al. 2005).

Table 25.1 Examples of diverse nitrogen-fixing bacteria associated with legume tree species useful in agroforestry systems

Bacterial symbiont	Host genus	Source
Allorhizobium undicola	*Acacia*	De Lajudie et al. (1998)
Azorhizobium caulinodans	*Sesbania*	Dreyfus et al. (1988)
Bradyrhizobium elkanii	*Faidherbia*	Wolde-Meskel et al. (2005)
B. japonicum	*Inga*	Leblanc et al. (2005)
B. liaoningense	*Erythrina*	Wolde-Meskel et al. (2005)
Ensifer mexicanus	*Acacia*	Lloret et al. (2007)
Mesorhizobium albiziae	*Albizia*	Wang et al. (2007)
M. plurifarium	*Acacia*	De Lajudie et al. (1998)
Rhizobium etli	*Gliricidia*	Hernández-Lucas et al. (1995)
R. gallicum	*Leucena*	Hernández-Lucas et al. (1995)
R. hainanense	*Tephrosia*	Chen et al. (1997)
R. multihospitium	*Robinia*	Han et al. (2008)
R. tropici	*Calliandra*	Zhang et al. (1991)
Sinorhizobium fredii	*Acacia*	Wolde-Meskel et al. (2005)
S. kostiense	*Prosopis*	Sprent (2009)

The global diversity of rhizobia is a black box owing to only 30% of the 728 genera (~19,325 species) of the *Fabaceae* and has been evaluated for nodulation (Sprent 2009). Several rhizobia have been recently described mainly from the tropical legume tree species, and based on their phenotypic characteristics, the diversification centres of host legumes are centred in the tropical region (e.g. Ethiopia, Kenya and Sudan) (Lie et al. 1987; Zhang et al. 1991; Nygren et al. 2012). The tropical soils in India have large population of rhizobia, which are capable of nodulating various legumes (Nambiar et al. 1988). Examples of diverse nitrogen-fixing bacteria associated with legume tree species useful in AFS is given in Table 25.1. Nearly 100 known legume-associated rhizobia do not show homologous clade denoting their functional diversity (Nygren et al. 2012). Fixation of nitrogen by tree species in association with nitrogen fixers leads to tripartite symbiotic system composed of plant, nitrogen-fixing bacteria and mycorrhizal fungi (Nygren et al. 2012). Interestingly, *Acacia koa* in tree canopies develops nodulation in adventitious roots in association with bradyrhizobia (Leary et al. 2004). It is likely such mutualistic association fixes atmospheric nitrogen when rhizosphere is under stress or perturbation. Until recently, it has been generally accepted that legumes are nodulated exclusively by the members of the family *Rhizobiaceae* in the *Alphaproteobacteria*, which includes the genera *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Rhizobium* and *Sinorhizobium* (Sprent 2002).

Over the last few years, several other species of *Alphaproteobacteria* have been shown to nodulate legumes (Moulin et al. 2002; Moreira 2008). These include strains of *Methylobacterium*, *Blastobacter*, *Devosia*, *Ochrobactrum* and *Phyllobacterium* (Araujo et al. 2012). A few members of *Betaproteobacteria* such as *Burkholderia*, *Ralstonia* and *Cupriavidus* have been discovered in nodules of tropical legumes (Araujo et al. 2012). Recently, the presence of *Gammaproteobacteria* of the genera *Pseudomonas*, *Pantoea*, *Enterobacter* and *Cohnella* has been described in the nodules of legumes (Araujo et al. 2012). Hence it is suggested to call the bacteria-forming nodules in legumes as legume-nodulating bacteria, instead of calling them as rhizobia.

At the outset, the symbiosis by actinorhizae in AFS is understudied (Nygren et al. 2012). *Frankiaceae* has wider association with forest tree species much greater than *Proteobacteria* and highly important in forests and AFS. Nitrogen-fixing symbionts belonging to actinomycetes (genus *Frankia*) are known to establish root nodules in around 280 nodulating nonlegume species (belonging to 25 genera) (Nygren et al. 2012). The actinorhizal plant species are known from forests, swamps, riparian zones, prairie and desert. Actinorhizal mutualistic associations spread over in wide range of plants and geographic locations (Arctic to the Tropics and from the semidesert to rainforests) (Russo 2005). The major tree species of importance in tropical AFS include *Alnus* (Betulaceae), *Casuarina*, *Allocasuarina* (Casuarinaceae) and *Hippophae* (Elaeagnaceae). It is known that 28 plant species in six families (Betulaceae, Casuarinaceae, Elaeagnaceae, Leguminosae, Moraceae and Myricaceae) are actinorhizal (Dinkelaker et al. 1995). Such widespread actinorhizal association with woody perennial tree species is of immense value in AFS.

None of the cyanobacteria seems to be involved in higher plant system relevant to AFS. However, understorey of the AFS may have many bryophytes which certainly harbour cyanobacteria contributing nitrogen fixation to enrich soils. Similarly, several bacteria are known to be endophytic in live tissues of tree species (bark, xylem, leaf and root), but their role in AFS is yet to be completely understood.

2.2 Non-symbiotic Nitrogen-fixing Bacteria

A wide variety of non-symbiotic nitrogen-fixing microbes is also a valuable component of AFS. It is known that about 25 genera of non-symbiotic bacteria possess the ability to fix atmospheric nitrogen (Desai et al. 2016). The plant growth-promoting rhizobacteria (PGPR) as bioprotectants have been divided into two groups: (i) those with biocontrol ability which indirectly benefit the plant growth and (ii) those that influence directly on plant growth and seed emergence (in turn improve crop yields) (Glick et al. 1999; Chauhan et al. 2015). The PGPR are also known to be beneficial in agroforestry as they stimulate growth promotion, provide pathogen resistance and produce valuable biochemicals.

Widely distributed and extensively studied PGPR candidates include *Bacillus* spp. and *Pseudomonas* spp. (Desai et al. 2016). The PGPR are known to produce many growth-promoting metabolites like auxin (*Pseudomonas denitrificans*), hydrocyanic acid (*Mesorhizobium loti*), indole-3-acetic acid (*Azospirillum brasilense*, *A. lipoferum*, *Bacillus cereus*, *M. loti*, *Rhizobium leguminosarum*, *Pseudomonas fluorescens* and *P. tolaasii*) and siderophores (*P. fluorescens* and *P. tolaasii*) (see Prasad et al. 2015).

2.3 Mutualistic Fungi

The major mutualistic fungi associated in plant species include arbuscular mycorrhizal fungi (AMF), ectomycorrhizal fungi (EMF) and endophytes. The AMF are distributed in a broad range of ecosystems from aquatic to desert habitats provide wide opportunity to adapt them in AFS (Bagyaraj 1992). The AMF as obligate/non-host-specific symbionts belong to phylum *Glomeromycota* with 3 classes (*Archaeosporomycetes*, *Glomeromycetes* and *Paraglomeromycetes*), 5 orders (*Glomerales*, *Diversisporales*, *Gigasporales*, *Paraglomerales* and *Archaeosporales*), 14 families and 26 genera (Sturmer 2012).

The importance of maintaining active populations of AMF in agroforestry soils to sustain crop productivity has been demonstrated by earlier workers (Dodd et al. 1990). Several reports are available on the influence of AFS on the AMF diversity and abundance. Most of these investigations have found that AFS have a positive effect on the AMF community (Lacombe et al. 2009; Pande and Tarafdar 2004; Prasad and Mertia 2005). Kumar et al. (2007) reported that AM colonization of crops was significantly higher under the tree canopy. It seems that the roots belonging to trees acted as source of inoculum for AM colonization of intercrops as AMF do not exhibit host specificity. Different tree species colonized by AMF in AFS varying in their effect to colonize the annual crops grown in association has also been reported (Mutabaruka et al. 2002; Shukla et al. 2010). Recently an experiment was carried out to study the effect of spacing of tree species on native AMF and microbial biomass carbon in the soil in an alley cropping system. The treatments comprised of three spacings (4, 8 and 12 m) between two tree species, *Leucaena leucocephala* and *Gliricidia sepium*, and three field crops, viz. finger millet, peanut and pigeon pea, grow between trees. All the three field crops grown between *Leucaena* had higher AMF propagules compared to those grown in between *Gliricidia*. The microbial biomass carbon in soil was more in all the three alleyed crops grown in between *Gliricidia*. Spacing of 12 m between trees supported most of the microbial parameters studied and the yield of all the three field crops. *Gliricidia* spaced 12 m apart considerably improved the yield of finger millet (Balakrishna et al. 2016).

The impact of land use intensity on AMF was investigated at six land use types, viz. natural forests, grasslands, acacia plantations, cardamom plantations, coffee plantations and paddy fields, in the Western Ghats in Southern India. At post-monsoon season, the root colonization, spore density, number of infective propagules and species diversity of AMF were significantly higher in natural forests and grasslands followed by plantations and least in paddy fields (Lakshmipathy et al. 2012).

Belowground microbial diversity, as influenced by coffee agroforestry systems was studied in the Western Ghats of India. Soil microorganisms in the rhizosphere of coffee (Arabica and Robusta) grown under one specialized shade tree species, multistorey coffee systems with two shade tree species and coffee with three or more species under moist deciduous and evergreen ecological conditions were investigated. Population of total bacteria, fungi, actinomycetes and nitrogen fixers were higher under evergreen ecosystem compared to that of deciduous conditions. Of the two species of coffee, Arabica harboured more bacterial population, AMF, N-fixers, P-solubilizers and cellulose decomposers, while Robusta harboured higher number of fungi and actinomycetes. Of the three typologies, coffee grown under two shade trees supported higher population of all microorganisms (Bagyaraj et al. 2015).

Based on 454 pyrosequencing in 17 boreal, temperate, subtropical and tropical forests, the AMF community was found to be dominant in tropical rainforests (Shi et al. 2014). The largest number of AMF and their diversity was seen in organically managed sites than those found in chemically managed sites indicating that chemically managed sites deprive AMF diversity and selectively support AMF forming small spores (e.g. *Rhizophagus* and *Funneliformis*) (Kumar and Adholeya 2016). *Rhizophora mucronata*, a typical mangrove tree species, was colonized by 18 species of AMF in southwest coast mangroves in India, while the woody legume climber *Derris triflorum* was colonized by as high as 34 AMF (Sridhar et al. 2011). The AMF are known to protect AFS from several pathogenic fungi (e.g. *Phytophthora*, *Gaeumannomyces*, *Fusarium*, *Thielaviopsis*, *Pythium*, *Rhizoctonia*, *Sclerotium*, *Verticillium* and *Aphanomyces*) and nematodes (*Rotylenchulus*, *Pratylenchus* and *Meloidogyne*) (see Barea et al. 2005).

The EMF is another important economically valuable component of the AFS. Up to seven EMF colonized *Acacia auriculiformis* and *Casuarina equisetifolia* growing in coastal sand dune in southwest coast of India (Ghate et al. 2014; Ghate and Sridhar 2016a). Similarly, the coastal sand dune forests in Brazil harboured EMF belonging to six genera (*Amanita*, *Coltricia*, *Lactifluus*, *Russula*, *Scleroderma* and *Tylopilus*) (Sulzbacher et al. 2013). In a mangrove stand of Southwest India, two EMF (*Inocybe petchii* and *Thelephora palmata*) were recorded (Ghate and Sridhar, 2016a). The EMF in 17 boreal, temperate, subtropical and tropical forests based on 454 pyrosequencing revealed the highest diversity in midlatitude, i.e. boreal and temperate forests (Shi et al. 2014). The ECM population was inversely correlated with plant species diversity attributing that high-level speciation occurred in less diverse forest ecosystems. Natarajan et al. (2005) recorded many EMF in the dipterocarp forest in Western Ghats of India. Among 157 macrofungi recorded in the Western Ghats forests (forest reserve, Shola forest, sacred grove and coffee agroforestry), 17 species were EMF (Karun and Sridhar 2016). In the protected forests of the west coast of India (arboretum and botanical garden), among 53 macrofungi, 10 species were ECM (Pavithra et al. 2016). In a similar study of macrofungi in the Southwest India, 25 species of ECM were recorded in three plantations (*Acacia*, *Areca* and *Anacardium*) and in an arboretum (Karun and Sridhar 2014).

Association of non-mycorrhizal fungi as endophytes with aerial and belowground healthy tissues of tree species is common, and their importance in plant protection is one of the current aspects of debate (Sridhar 2009, 2012; Selim et al. 2012). Inventory on their association with AFS is highly valuable and will provide further dimension to the importance of such fungi in plant protection, plant growth promotion and production of fungal metabolites (see Sridhar 2016). Endophytic fungi associated with 68 various host plants including potential tree species are useful in AFS (Kaushik et al. 2016). Saucedo-García et al. (2014) studied the relationships between coffee agroforestry systems and biodiversity of endophytic fungi and noted that the endophytic fungi serve as potential management tools to prevent pests and pathogens of coffee plants. The 454 pyrosequencing of soil fungi in 17 boreal, temperate, subtropical and tropical forests revealed dominance of non-mycorrhizal fungi in the subtropical forests (Shi et al. 2014). Another potential root endophytic basidiomycete *Piriformospora indica* has high potential in plant growth promotion in a variety of tree species useful in AFS (Varma et al. 1999).

3 Management of Microbial Biodiversity

Management of microbial biodiversity assumes utmost importance in practicing and supporting AFS. There is ample scope to tune the microbial diversity towards sustainable AFS to reap desired agricultural products. There are various eco-friendly practices than the conventional strategies, and those could be employed to support the microbial biodiversity to achieve sustainable AFS (Fig. 25.1). The chemical management (e.g. synthetic fertilizers and pesticides) of monocultures with extensive tillage deteriorates soil, deprives microbial diversity and leads to limited/impaired ecosystem services. On the other hand, organically managed polyculture practice in AFS with least disturbance supports soil fauna, enriches soil, boosts microbial diversity and leads to sustainable ecosystem services. The following subsections address the impact of AFS, role of co-occurrence, influence of abiotic factors and effect of perturbation.

3.1 Impact of Agroforestry Systems

Different types of AFS have varied impacts on the microbial diversity. For instance, the root system of tree species in AFS is also important to conserve microbial diversity as well as soil quality. Functional compatibility of tree species of AFS with those of microbial community is important in practicing AFS. Sustainability in agroforestry could be achieved by considering tree-based intercropping as conventionally managed agricultural systems have negative impact on the abundance and diversity of AMF (Bainard et al. 2011).

Actinorhizal *Casuarina* plantations have reached over 1.4 million ha globally, while up to 0.8 million ha of such plantations are confined to tropical regions (see Russo 2005). It is known that up to 300,000 ha of *Casuarina* plantations are established in coastal region of South China to prevent coastal erosion (Bai and Zhong 1996). Such attempts are also in practice in the Southwest Indian coastal region. The question remains how to establish AFS encompassing *Casuarina* species? In the coast of Kenya, 26 tree species and grasses around *Casuarina equisetifolia* have been established (Russo 2005). However, litter of *C. equisetifolia* possesses allelopathic effects, which prevents germination and seedling growth of rice and cowpea

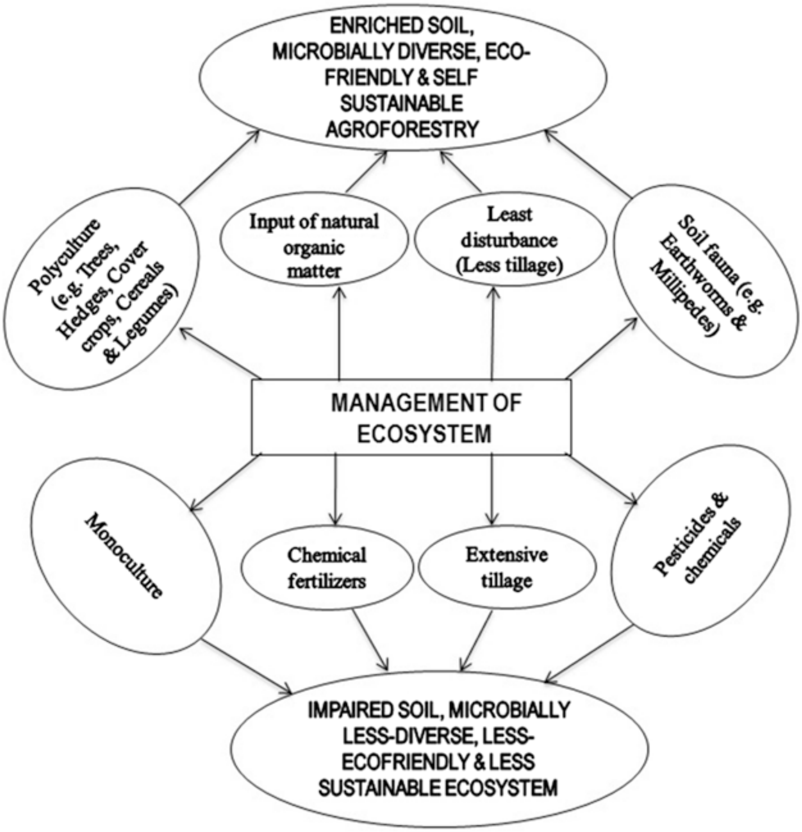

Fig. 25.1 Scheme of management of ecosystem towards conservation of microbial biodiversity for sustainable agroforestry

(Jadhav and Gaynar 1995). If that is the situation, composition of tree species and planting density of each tree species needs more attention. For example, if neem (*Azadirachta indica*) is cultivated along with *Acacia*, the latter tree species takes over as it grows fast, thus planting density needs more attention.

Sprent (2005) provided detailed account of nodulated legume trees useful for AFS. Based on survey of the entire coastal belt of the Indian subcontinent, Rao and Meher-Homji (1985) gave a broad outline on the tree species suitable for AFS. Experiments carried out in different land use systems in Amazon (native forest, agroforestry, pasture system and intercropped system) soils in agroforestry were equivalent to native forest in carbon management through biodiversity (Silva et al. 2014).

The *Alnus acuminata* has been cultivated mainly in Colombia and Costa Rica, and in Costa Rica its cultivation along with coffee for shade has history of more than a century (Russo 2005). Siderophore-producing *Bacillus megaterium* in tea rhizosphere improved growth and reduced disease intensity (Chakraborty et al. 2006).

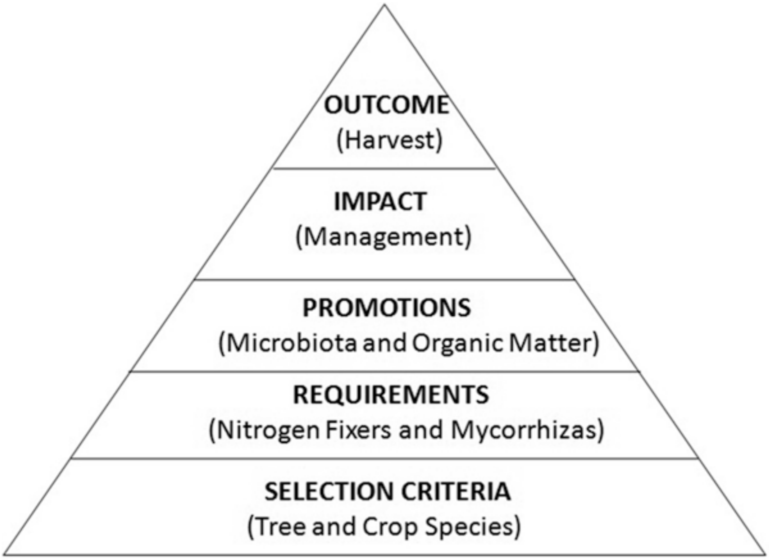

Fig. 25.2 Management strategies necessary towards microbiologically diverse sustainable agroforestry system

Inoculation of AMF to micropropagated plantlets (e.g. apple, asparagus, avocado, banana, coffee, grapevine, kiwi, pineapple, raspberry and strawberry) after hardening improved vigour as well as growth (Yao et al. 2002; Bagyaraj 2014). Interestingly, 10-year-old mulberry and 1.5-year-old papaya trees responded positively to inoculation of AMF (Mamatha et al. 2002). Endophytic diazotrophs associated with Gramineae (forage grasses), coffee and banana contributed substantially in AFS (Herridge et al. 2008; Fuentes-Ramírez et al. 2001; Martínez et al. 2003). Non-symbiotic cyanobacteria and fungi are also important components in soil or in canopy of AFS.

3.2 *Mutual Effects*

In AFS, mutual impacts of tree species with those of associated microbiota are important for sustainability. The pyramid in Fig. 25.2 explains the strategies needed to be undertaken in practicing AFS: (i) the selection criteria for AFS (e.g. tree species and crop species) is the first step; (ii) the second step is the requirement of selection of diverse microbiota (e.g. nitrogen fixers and mycorrhizal fungi); (ii) the third stage needs input of biofertilizers (e.g. microbiota and green manure/organic manure); (iv) management or assessment of impact is the major criteria in the fourth step; and (v) the last step constitutes outcome of AFS (e.g. harvest without major perturbations).

The *Rhizobium* and AMF colonize the root simultaneously without competing for the sites of colonization, but pre-colonization may depress development of co-partner mainly for carbohydrates owing to limited photosynthesis, as AMF take edge over *Rhizobium* (Bethlenfalvay et al. 1985; Brown and Bethlenfalvay 1987). Such tripartite interactions among plant species, *Rhizobium* and AMF have positive impact especially under drought conditions (Ruiz-Lozano et al. 2001). Association of AMF with rhizobia reveals that AMF favours nodulation and they produce phytoalexins, isoflavonoids and flavones, which induce nod gene expression (Desai et al. 2016). Positive interactions between AMF and non-symbiotic bacteria and phosphate-solubilizing bacteria have been reported by Desai et al. (2016). Rhizobia as well as PGPR influence AMF function, while AMF can influence the population of rhizobia and PGPR in the rhizosphere zone (Barea 1997). Dual inoculation of PGPR and AMF leads to positive impact on growth of crop plants (Desai et al. 2016). The AMF are well known for uptake of diffusion-limited minerals from soil (e.g. Cu, P and Zn). Besides they confer resistance to host by pathogens, produce hormones and provide ability to host to withstand drought stress and compatible with growth-promoting rhizobia in soils (Bagyaraj 2011, 2015).

A wide variety of tree species in coastal regions of India are colonized by AMF, EMF and endophytic fungi (see Sridhar 2016). Observation on mycorrhizal fungi in coastal forests (e.g. coastal sand dunes and mangroves) provides further insights on their ability to support forest ecosystem to tolerate salinity and disturbance. Tripartite mutualistic associations of tree species, *Frankia* and mycorrhizas have also been reported: *Frankia* + AMF in *Alnus* spp., *Casuarina equisetifolia* and *Ceanothus velutinus* (Rose and Trappe 1980; Rose and Youngberg 1981; Gauthier et al. 1983). Actinorhizal *Casuarina* spp. are also associated with EMF like *Pisolithus* and *Scleroderma* (Warcup 1980; Dell et al. 1994; Russo 2005; Ghate et al. 2014; Ghate and Sridhar 2016b). In actinorhizal *Alnus acuminata*, the EMF *Gyrodon monticola* as well as *Phylloporus caballeroi* were associated (Singer and Gomez 1984). There are several possibilities of tripartite or higher levels of association in actinorhizal plant species (e.g. tree species + *Frankia* + AMF + EMF) as consortium of microbiota exists in the rhizosphere. Investigations on interactions of belowground tree-crop-microbiota in management of nitrogen fixation in AFS need further scrutiny (Nygren et al. 2012). Soil macrofauna (e.g. earthworms, millipedes and termites) also have major role in enhancing the biodiversity as well as dissemination of microbes in the AFS (León et al. 2006; Ambarish and Sridhar 2014). Termites possess nitrogen-fixing facultative Gram-negative bacillus (*Citrobacter freundii*) which is also a valuable mutualistic association in AFS. In natural tropical forests, termite association is found in almost all tree species which are involved in the decomposition of lignocellulosic material and are also known to cultivate edible macrofungi (e.g. *Termitomyces* spp.).

Soil aggregation by microbes in the AFS is an important event in soil stabilization and erosion prevention. Bacteria, algae and fungi are involved in soil/sand aggregation (Forster and Nicolson 1981). Evaluation of sand aggregates in coastal region consists of diverse microbiota (e.g. *Bacillus* spp., *Pseudomonas* spp., *Nocardia* spp., *Streptomyces* spp. *Aspergillus fumigatus*, *Penicillium* spp. and *Glomus fasciculatum*). In addition to green algae, cyanobacteria (*Nostoc* spp.) were recovered from the sand aggregates, and their nitrogen-fixing ability increased other microbial activity (Forster 1980; Forster and Nicolson 1981). In addition to bacterial, algal and cyanobacterial polysaccharides, the AMF produce β-1-3-glucan and the glycoprotein glomalin which are also involved in soil/sand aggregation (Lemoine et al. 1995). It is known that the stable soil aggregates are responsible for aeration and retention of moisture necessary for growth of plant species (Oades 1984).

3.3 Edaphic/Abiotic Factors

Abiotic and soil edaphic factors are important to support the AFS in different geographical locations. Microbial diversity in soil samples obtained from eight AFS in Southeast India showed positive correlation with many soil edaphic factors (e.g. organic carbon, moisture, nitrogen, phosphorus and microelements) which rely mainly on organic matter, vegetation and soil nutrients. Soil samples collected from 17 forests along a latitudinal gradient (boreal, temperate, subtropical and tropical) subjected to pyrosequencing revealed soil microbial communities are strongly influenced by the abiotic and biotic factors (Shi et al. 2014). The soil fungal community composition was found to be strongly influenced by temperature, latitude and plant diversity with highest diversity seen in midlatitude. Special attention is necessary to follow the abiotic and edaphic conditions of a specific geographical area to manage AFS. For instance, in *Ginkgo* tea AFS activities of soil enzymes (catalase, dehydrogenase, urease, protease and invertase) were significantly correlated with soil organic carbon as well as total nitrogen (Tian et al. 2012).

3.4 Perturbation

Due to continuous cultivation of single crop using agricultural chemicals spoils the soil health, and it is also detrimental for soil microbial diversity. High population and diversity of AMF were seen in organically managed AFS than those managed chemically, and the latter situation deprived AMF diversity and supported only small spore-forming AMF (e.g. *Rhizophagus* and *Funneliformis*) (Kumar and Adholeya 2016). Plant species in coastal regions of India are colonized by AMF, EMF and endophytic fungi (see Sridhar 2016). Mutual association of such microbes with tree species in coastal sand dunes/mangroves may help to withstand the impact of disturbances (e.g. variations in salinity, temperature fluctuations, tidal effects, shifting sand and sand abrasion). The agroforestry practices employed in agricultural field work similar in mangroves, coastal sand dunes or marine-influenced ecosystems need investigation. As mangrove ecosystems have been encroached for agriculture, the question remains that any sustainable AFS could be established, partially protecting mangrove/mangrove-associated plant/tree species along with agriculturally valuable crop/tree species.

According to Connell's (1978) hypothesis, moderate disturbance enhances the diversity in an ecosystem (see Beena et al. 2000). Too low disturbance and too high disturbance depriving the microbial diversity suggest tuning activities in AFS at moderate level to maximize benefits by microbial diversity. Rehabilitation of perturbed landscapes (e.g. mining sites, industrial sites with heavy metals, soils degraded with agricultural chemicals and eroded landscapes) need special attention to raise AFS. For example, *Alnus acuminata* is one of the fast-growing tree species valuable for wood, which improves soil fertility and helpful to reclaim wasteland/impoverished soils possessing pH below 4.5 (Russo 2005).

Monocrop systems are known to have negative impact on the abundance and diversity of soil-inhabiting fungi. The AMF in soil are known to produce resting spores (chlamydospores), which have the capability to withstand adverse conditions and germinate under favourable conditions and are thus most suitable for AFS. The EMF are also known to enhance the tolerance of tree species to acidic pollutants as well as increased toxic elements in soils (Brunner 2001). To rehabilitate highly perturbed landscapes, initially monoculture could be followed. Once the monoculture stabilizes, management should be enforced by shifting the monoculture towards polyculture by thinning and incorporation of other suitable tree species. This will make the AFS more sustainable.

4 Evaluation

Microbial diversity in AFS is the focal issue, and its monitoring or evaluation will help to understand as well as develop strategies required to improve the status. Some basic questions need to address on the evaluation of diversity of AFS include:

1. Does the microbial diversity of soil represent the status of an AFS?
2. Will such evaluation methods are universally applicable to different AFS?
3. What are the minimum biodiversity values/standards required to monitor the status of an AFS?
4. Does soil quality monitoring of AFS (in turn the soil microbial diversity) serve as indicator of various degree of soil health like recovered, disturbed and impoverished?

Various techniques encompassing simple to sophisticated methods (structural, genetic and functional profiling) to assess microbial community in soil have been reviewed by Sharma et al. (2010).

4.1 Structural Profiling

Structural profiling relates to measurement of species, genera and communities of an ecosystem, which are sensitive to environmental changes resulting in shift of composition (Avidano et al. 2005). Phospholipid fatty acids serve as potential bioindicator in elucidating the microbial community and in turn soil health as it is common structural component of a wide variety of microbes (e.g. bacteria, actinomycetes and fungi, including mycorrhizal fungi) (Zelles 1999). Jesus et al. (2009) have observed differences in structure and composition of bacterial community related to alterations in soil attributes owing to land use pattern.

Association of AMF in AFS is highly dependent on the host plant species, land use pattern and management practices (Kling and Jakobsen 1998). This association is very sensitive to pollution like heavy metals, organic pollutants and atmospheric deposition (Egli and Mozafar 2001). Enrichment of soils with nitrogen shifts large spore-bearing species of AMF (*Gigaspora* and *Scutellospora*) with those small spore-producing AMF (*Glomus* spp.) (Egeston-Warburton and Allen 2000). Hence, assessment of AMF spores (in soils and habitats) and root colonization by AMF forecasts the health of an ecosystem.

For the first time, *Frankia* was isolated from nodules of *Comptonia* following enzymatic method (Callaham et al. 1978). Later, other methods like serial dilution, selective incubation, osmium tetroxide treatments and sucrose density gradient centrifugation were employed for evaluation of *Frankia* (Baker and Torrey 1979; Lalonde 1979; Lalonde et al. 1981; Quispel and Burggraff 1981).

4.2 Genetic Profiling

The genetic diversity profiling techniques encompass several molecular methods, and the most commonly used method includes DNA gene coding for rRNA (e.g. 16S rRNA for bacteria and 18S rRNA for fungi), which helps designing primers targeted to different groups of bacteria and fungi. In addition, PCR followed by denaturing gradient gel electrophoresis (PCR-DGGE), temperature gradient gel electrophoresis (PCR-TGGE), terminal restriction fragment length polymorphism (T-RFLP), single-strand conformation polymorphism (SSCP) and amplified ribosomal DNA restriction analysis (ARDRA) are the methods for microbial community assessment (see Sharma et al. 2010). Molecular tools like 18S rRNA gene PCR could also be applied for precise assessment of soils and habitats for AMF (Chelius and Triplett 1999).

High-density, high-throughput and microarray-based genomic techniques serve to monitor microbial community structure, function and dynamics more elegantly. The DNA microarray technology helps in identifying an unknown nucleic acid (as targets) mixture by hybridization to many known diagnostic nucleic acids (as probes), which are immobilized in an order on a mini solid surface (Loy et al. 2006).

More than 30,000 probes are known to detect unknown nucleic acid under two main categories [Phylochips; Functional Gene Arrays (FGAs)] (Wilson et al. 2002; Zhou 2003; Taylor et al. 2007). Similarly, *GeoChip 2.0* could be employed for ecological applications especially to detect carbon and nitrogen cycle genes across a variety of samples, locations and vegetation types worldwide. The most sophisticated method to assess biodiversity is 454 pyrosequencing, which depends on the detection of pyrophosphate release on nucleotide incorporation (Metzker 2005).

4.3 Functional Profiling

The functional profiling techniques for soil microbial community assessment include expression of functional activities like decomposition of organic carbon, nutrient turnover and plant growth promotion under the influence of soil edaphic conditions (Giller et al. 1997). Carbon utilization patterns as well as enzymatic activity of bacterial community are useful to evaluate different soils (Nielsen and Winding 2002). Moreover, metabolic profile using Biolog, MicroResp (Campbell et al. 2003) and substrate-induced respiration (SIR) (Degens and Harris 1997) serves as fingerprinting of microbial community functioning. In addition, assessment of soil enzyme diversity also serves as good approach to examine functional diversity (Kandeler and Böhm 1996). Substrates like Remazol brilliant blue, p-nitrophenol (pNP) and/or tetrazolium salt coupled with specific compound of interest (e.g. cellulose and phosphate) serve to assess microbial functional diversity (Wirth and Wolf 1992). The pNP-linked substrates (e.g. β-glucopyranoside, N-acetyl-β-D-glucosaminide, β-D-cellobioside and phosphate) are highly valuable as the only one method that could be employed for all enzyme analysis. For example, in *Ginkgo* tea AFS soil organic carbon, total nitrogen, microbial biomass and the enzyme activities were significantly higher than pure tea ecosystem, while soil enzyme activities (catalase, dehydrogenase, urease, protease and invertase) were highly correlated with soil organic carbon and total nitrogen (Tian et al. 2012).

4.4 Minimum Data Set

For a fair assessment of AFS, minimum data set (MDS) is one of the basic requirements, meaning a set of specific soil quality measurement values (Doran and Parkins 1996). Those MDS should be (i) compatible with ecosystem processes and physical or chemical indicators, (ii) sensitive to acceptable time frame, (iii) ease of assessment, (iv) robust methodology with standard, (v) cost-effective and (vi) relevant to goals like food production, food security and sustainability (Bunning and Jimenez 2003).

5 Outlook

Microbial diversity constitutes the largest underexplored biota on the earth. There is huge gap between demand and production of microbial inoculants. This could be met by screening and selecting effective microbial consortia (consisting of AMF and PGPR) for trees and crops used in AFS. These effective microbial consortia selected can be used for inoculation in AFS. A wide variety of tree species compatible to a specific geographical region is available to support AFS to improve the economic gains (e.g. root-nodulating plants, medicinal plants, resin-yielding plants, plantation crops and horticultural crops). Input of organic matter into the soil as source of energy by the AFS enhances the microbial diversity leading to breakdown of organic matter, nitrogen fixation, uptake of essential minerals and protection against soilborne plant pathogens. Such activities stabilize the AFS in favour of production, which needs long duration. It is necessary to exploit the capacity of microbes in AFS fully using multiple strain combination. Formation of soil aggregates by the impact of microbes also influences microbial diversity, and it may serve as an authentic indicator of soil health. Global coordinated approaches to evaluate the biodiversity of microbes in region-wise and AFS-wise will yield valuable result towards greater understanding as well as tackling problems related to microbial diversity under AFS in broader geographic scale.

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Chapter 26
Soil Microarthropods: Biodiversity and Role in Grassland and Agroforestry Ecosystems

Sharmila Roy, M. M. Roy, Ruquaeya Bano, and Pradeep Saxena

Abstract A variety of organisms inhabit soil; many of them are still unknown. Each organism has a specific role in the complex web of life in the soil. They are mainly responsible for soil organic matter turnover and nutrient cycling through a diversity of processes. The microarthropods are mostly soil or litter dwellers and transform plant litter physically and chemically into substances amenable to further degradation by microflora and vice versa. Grassland and agroforestry systems on account of their perennial nature harbour a wider diversity of soil biota in comparison with agricultural systems. The interactive effects of soil biota and grassland/agroforestry systems are not understood to the desired levels. Also, there is little research on the role of soil biota in various other land use systems. Now, soil degradation has emerged as a global problem that leads to desertification, erosion and depletion of fertile lands. This has led to an in-depth look into reliable scientific information on soils, especially the biodiversity and many services they provide. It has created a demand for agricultural practices that are less dependent on external inputs, tighten nutrient cycles and are productive without degrading soil. The available work on soil organisms, especially the grassland and agroforestry systems from tropical areas, is reviewed, and some future thrust areas are suggested.

Keywords Acari · Collembola · Diversity and dynamics · Land use management · Vegetation diversity · Soil properties · Microarthropods

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1 Introduction

Soil is the natural medium of plant growth, providing habitats to innumerable organisms. The plant, soil and associated organisms are interacting since the first plant has originated and the food web developed around it (Lussenhop 1992). Soil organisms occupy only 0.5% of total soil volume. Out of this living component, 5–15% is represented by micro-organisms (bacteria, protozoa, etc.) and macro-organisms (termites, earthworms, ants, etc.), and the rest 85–95% is occupied by plant roots. As per an estimate, 1 g of soil contains up to 1 billion bacteria cells consisting of tens of thousands of taxa, up to 200 m fungal hyphae and a wide range of mites, nematodes, earthworms and arthropods (Brussard 1998). This vast subterranean diversity contributes to the aboveground biodiversity and biomass (Wardle et al. 2004). Similarly, the high aboveground plant diversity results to high litter yield, and this resource heterogeneity adds to belowground diversity (Hoopper et al. 2000). Soil ecosystem in general supports greater biodiversity than the aboveground system (Bardgett et al. 2005). At micro-scale (individual sample) soil climate, root zone aggregates are the main factors, while at the mesoscale (plots), type of debris or soil disturbance intensity governs their distribution. Their distribution and dynamics at landscape (macro) level is guided by the topography, plant cover, soil type, soil carbon, etc. (Berg 2012). The numerous interactions of soil organisms depend on variation in soil profile, resource availability, microclimate, chemical and physical structure, etc. The distribution of soil biota is often patchy, and the competition for the resources leads to intricate detrital food web.

The energy and nutrients required for plant growth are found locked in the dead organic materials in the soil; their release is critical for system productivity. Soil organisms play vital role in this process. Each organism has a specific role in the complex web of life in the soil. The microarthropods comprise significant share of soil organisms. In fact, they are the dominant and integral part of soil food web and occupy all the trophic levels, perform vigorous role in the nutrient cycling processes and thus help in maintaining soil fertility, health and production of terrestrial ecosystems whether natural like grasslands/forests or man-made systems like agriculture and agroforestry.

Globally, grasslands occupy almost one fourth of terrestrial land spaces. They develop where rainfall is around 600 mm or less, not enough to produce a forest and not so less that the land develops into a desert. In true grasslands, vegetation is dominated by grass and grasslike species; only few trees are found. This permanent plant cover provides habitat, abundant nutrient supply and congenial soil environment from extreme weather condition for the faunal biodiversity which in turn provide a number of ecosystem services like water and nutrient cycle (support service), food production (provisioning), etc. The anthropogenic activities have substantial and often irreversible changes in grassland ecosystems (Vanbergen et al. 2007). The conversion of grasslands and forests into agriculture lands, urbanization, etc. degrades the soil and its capacity to support desired biodiversity.

The incorporation of trees and crops that are able to biologically fix nitrogen is fairly common in tropical agriculture systems (agroforestry). The role of agroforestry in enhancing and maintaining long-term soil productivity, sustainability and ecosystem functioning is well known (Jose 2009). The trees enhance soil physical, chemical and biological properties by adding significant amount of above- and below-ground organic matter and releasing and recycling nutrients in agroforestry systems (Jose et al. 2004; Nair 2008), biodiversity conservation (Kremen 2005; Kabir and Webb 2009) and support to soil biological diversity (Moco et al. 2010; Lakshmi and Joseph 2016).

In this paper, an account of soil microarthropod diversity and their role in detrital food web is discussed, especially in context of grassland and agroforestry systems as these organisms are less understood when compared to other category of soil organisms. Some future thrust areas are also suggested.

2 Soil Environment and Organisms

The soil as habitat regulates soil biological diversity. Most of the life forms occur in the topsoil (A horizon) layers which contain organic matter. The acclimatization to living, moving and feeding in soils has generated a wide range of diversity of life forms. Like other organisms, soil life forms occupy different soil ecological niches. These niches are determined by the soil physical structure (porosity), availability of nutrients, water (soil moisture), environment (temperature, pH) and chemical composition (Van Straalen 1998).

Soil organisms employ different strategies to survive and prosper in various environments. That may be combative strategies (c-selected) which maximize occupation and exploitation of resources under non-stressed conditions, stress strategies (s-selected) which allow survival and endurance of continuous stress environment and ruderal strategies (r-selected) that is characterized by a short span with a high reproductive potential which often enables success in severely disturbed situations. These three strategies can merge to give secondary strategies (C-R, S-R, C-S and CSR) which form part of a continuum with transition zone between them (Bardgett and Cook 1998).

All the living activities in soil are confined to different soil spheres. These spheres have distinct properties which regulate interactions among organisms at spatial and temporal scales. The biologically active soil spheres may be divided into detritosphere, porosphere, drilosphere, rhizosphere and aggregatosphere. The detritosphere comprises of litter, faeces and casts. The sphere provides habitat for mycorrhizal activity and grazing by the soil fauna. The detritospheres are nested with small patches of well-aerated organic matter which attract burrowing insects, earthworms and other macrofauna that makes the drilosphere. The porosphere is

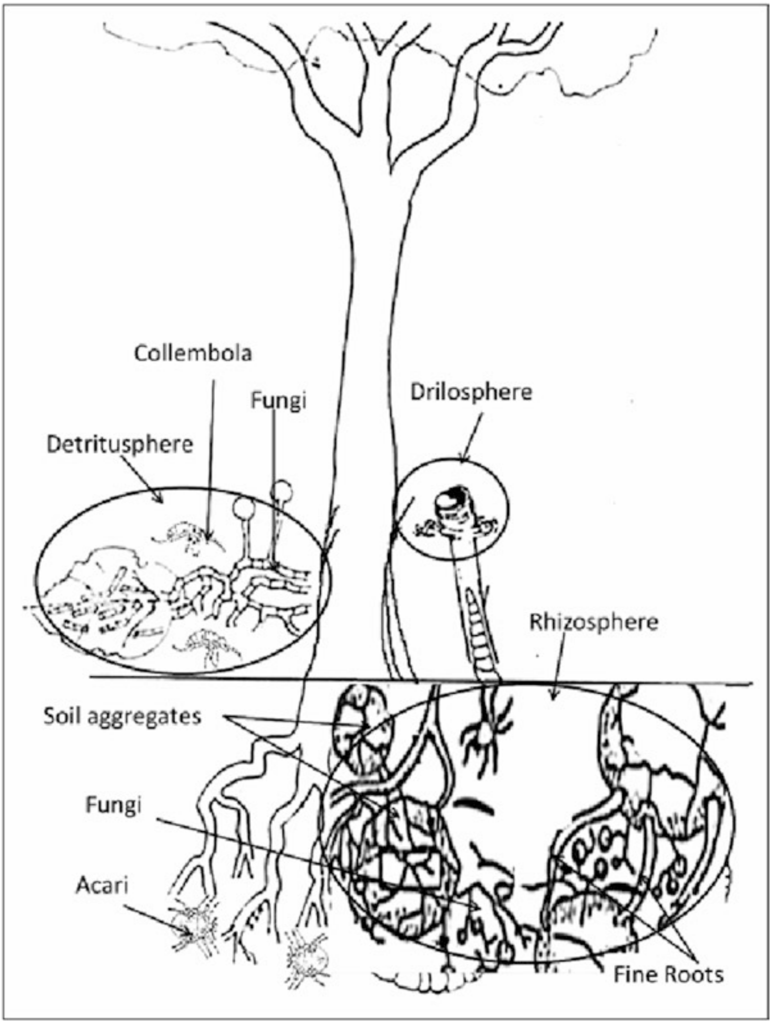

Fig. 26.1 Diagrammatic view of biologically active soil spheres (Modified from Veeresh and Rajgopal 1983)

created by plant roots that affect soil bulk density, water and dissolved nutrient availability. The roots, water films, pores and voids between soil aggregates form aggregatosphere. The root surface is termed as rhizosphere. The microarthropods and other soil microflora and fauna occupy spaces between the aggregates and around rhizosphere, the hotspots of activity due to the direct availability of plant exudates, food resources and congenial environment (Fig. 26.1).

2.1 Taxonomical Alignment

Taxonomically all living groups are well represented in soil (Fig. 26.2). The free-living components of soil detrital food web are bacteria, fungi and the fauna. Bacteria are the most abundant group of micro-organisms in soil, probably half of the total microbial biomass in the soil. Their population ranges from one hundred thousand to several hundred million per gramme of soil, depending on the condition of the soil. Fungi are primarily responsible for the decomposition of organic residues. Actinomycetes are commonly regarded as an intermediate group between the bacteria and fungi.

Free-living protozoa in soil feed on dissolved organic substances and on other organisms. Many feed wholly by grazing and predation. They depend primarily on bacteria as food and directly affect the structure of microbial communities. After the protozoa, nematodes are the second most dominant group of soil fauna in terms of numbers and biomass. Most of the terrestrial nematodes are <2 mm long and 0.05 mm wide. Nematodes feed, move and reproduce like protozoa in water films around soil particles. The density of gastropods, isopods, diplopods and chilopods are relatively low because of their sensitivity to soil environmental fluctuations.

The most abundant soil arthropods, in terms of number of individuals and species, are the acarines (mites) and collembolans (springtails). The predominant macroarthropod populations are coleopteran and hymenoptera. The macrofauna, viz. earthworms, ants and termites, do fragmentation and transportation of organic matter in deeper soil layers. Many small soil-dwelling invertebrates, such as millipedes, nematodes, centipedes, mites, annelids, spiders, insects, etc., have their effect on the physical and chemical properties of soil and debris and on the structure of microbial communities. The burrowing vertebrates like moles, rabbits, snakes, etc. are the habitat manipulators that create special niches for other organisms.

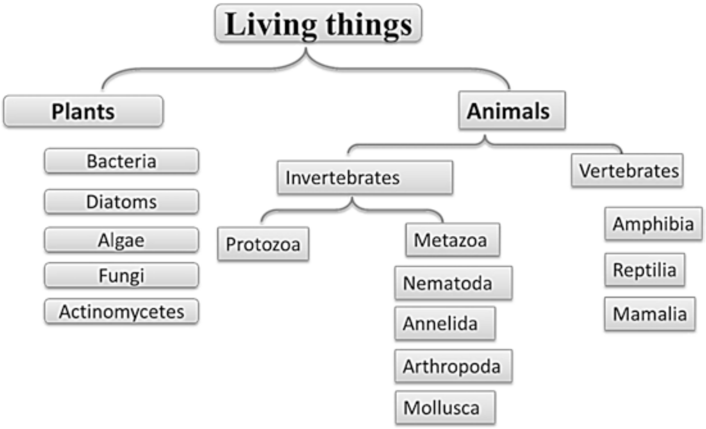

Fig. 26.2 Taxonomical representation of life forms in soils

2.2 Dwelling Habits

Soil organisms may be categorized on their dwelling in different soil layers. For example, organisms that live in the vegetation layer or on surface of soil are termed as epigeon; those living in the soil (edaphic layer) are categorized as hemiedaphon; organisms living into the organic layer of soil are enedaphon (Fig. 26.3). Further, based on moisture affinity, the hemiedaphon may be subdivided into hydrophile, mesophile and xerophile.

The soil arthropods can be distinguished based on their period/stages of life cycle spent in soil. The permanent inhabitants of soil are termed as geobionts (Fig. 26.4). The geophiles temporarily live in soil as adults or undergo part of their development, as eggs or larvae, in the soil. The individuals of order Coleoptera, Thysanoptera, Heteroptera and Diptera represent the group.

The geophiles may further be distinguished as the inactive and active ones. Inactive geophiles include adult insects which seek the shelter afforded by loose or decaying leaf litter/wood and, in surface soil, have little or no contribution in soil structure. The active geophiles pass different stages of development in soil and are closely associated with soil. They may be periodic and temporary based on their period of presence in soil (Singh and Lal 2001).

2.3 Size Categorization

The size classification of soil organisms may or may not be based on the soil pore spaces. It is one of the most commonly used classifications of soil organisms. On the basis of body width, they are grouped as micro-, meso-, macro- and mega-organisms

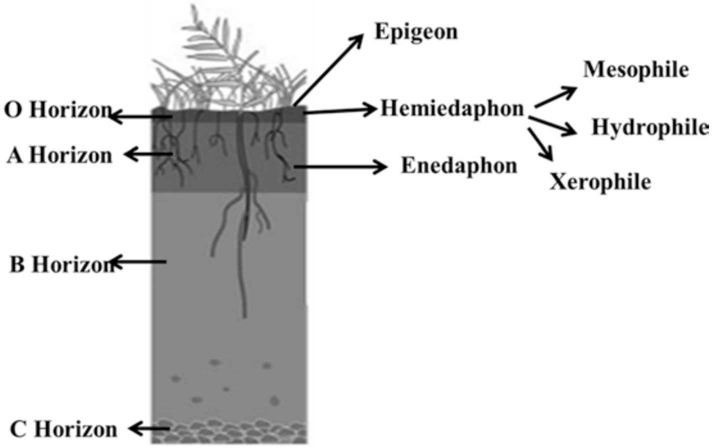

Fig. 26.3 Soil biota characterization as per their dwellings in different soil profiles (Picture modified from https://www.qld.gov.au/environment/land/soil/soil © The State of Queensland 2016)

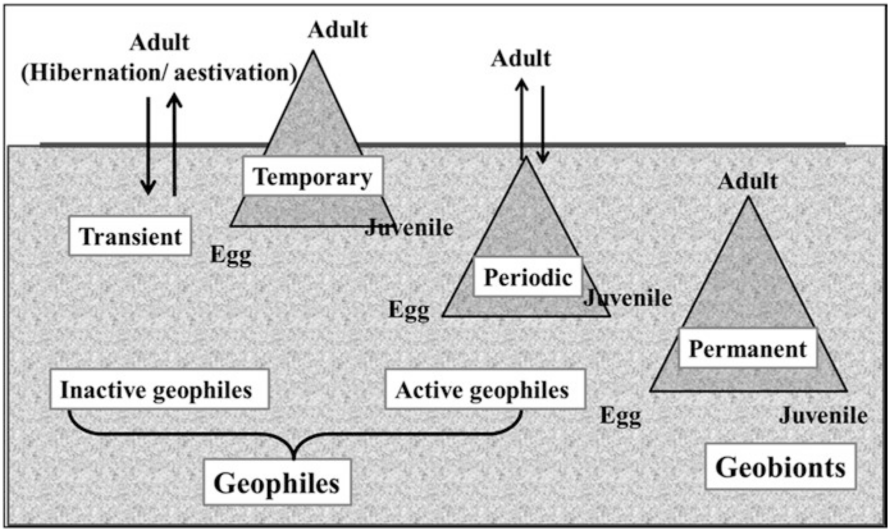

Fig. 26.4 Soil arthropods classified based on their period of presence in the soils (Source: Wallwork 1970)

Table 26.1 Size classification of soil organisms

Groups	Body size	Representative organisms/taxa
Microflora	<100 μ	Bacteria, algae, fungi, actinomycetes
Microfauna	<100 μ	Protozoans, nematodes
Mesofauna	100 μ–2 mm	Collembolans, acarines, proturans, diplurans, enchytraeids, larva of higher-order insects
Macrofauna	2 mm–20 mm	Earthworms, isopteran, molluscs, arachnids, isopods, myriapods, oligochaetes, coleopterans, etc.
Megafauna	>20 mm	Molluscs, myriapods, oligochaetes, vertebrates

(Table 26.1). In terms of feeding activity, the soil arthropods can also be classified as carnivores, phytophagous, saprophagous, symbionts, omnivores or microphytic feeders.

3 Diversity in Microarthropods

Microarthropods are small invertebrates; body size ranges from 0.2 to 10.0 mm. They are considered as members of soil mesofauna, mostly microscopic and require special methods and techniques to sort from soil. They include Protura, Diplura and Collembola of class Insecta; Symphyla and Pauropoda of class Myriapoda; Tardigrada, Copepoda and Isopoda of class Crustacea; and Pseudoscorpiones, Araneae and Acari of class Arachnida (Fig. 26.5).

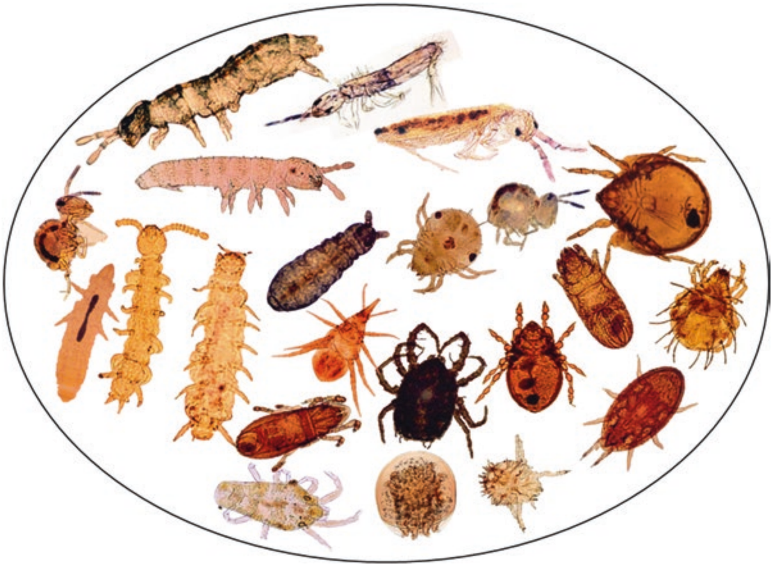

Fig. 26.5 Biodiversity in soil microarthropods

The most abundant soil microarthropods, in terms of number of individuals and species, are the acarines (mites) and collembolans (springtails). Springtails are wingless insects that have a segmented body of 0.2–6 mm with specialized appendages, including a springlike tail used for jumping. Worldwide, approximately 6500 species are listed, belonging to 18 families (Hopkin 1997). Most species are soil or litter dwellers, while only few species live on the surface or on the vegetation (mainly Entomobryidae and Symphypleona). In mature soil, their abundance may range 50–100,000 individuals m^{-2}. Protura and Diplura are also wingless insects and resemble to collembolan. Protura feed by sucking on the outer coating of fungal hyphae. They prefer organic soils and are reported scarcely from grassland soils. The diplurans represented by two families (Campodeidae and Japygidae) are also scarce in grassland soils. They are predatory in nature, feeding on small fauna. They also scavenge dead organic matter, grass roots, etc.

Pauropods are whitish up to 1 mm in size and feed on decaying plant materials, fungi and carrion. Some species may be predatory in nature. The Symphyla are 1–8 mm in length and prefer organic loam soils. They feed on living plant tissues. Tardigrada and copepod are abundant in moist forest floors and play an important role in leaf litter and wood residue decay.

Spiders and pseudoscorpions are the predaceous arachnids. Mites are the most abundant arthropod living in soil. Their density in forest soils can reach hundreds of thousands of individual m^{-2}. However, mites often go unnoticed because of their small size (μm) (Peterson and Luxton 1982). About 50,000 mite species are known, but it is believed that up to one million species could be in this group.

Most of these groups can be identified to order and family levels with the help of standard references. The specialized keys and pictures for species level identification are now available on many web pages (http://www.zoology.ubc.ca/~srivast/mites/key.html; http://www.collembola.org/projects/imagproc.htm; http://bugguide.net/node/view/258362; http://www.ncbi.nlm.nih.gov/pubmed/7663755; http://www.nhm.ac.uk/our-science/our-work/biodiversity/acari-research.html; http://www.publish.csiro.au/web_cds_demo/mites/ userguide.htm), etc.

4 Functions of Microarthropods

The energy and nutrients required for plant growth are found locked in the dead organic materials in the soil. The release of these nutrients and energy is critical for a system (Wardle et al. 2004). The soil biodiversity and their community structure perform different functions in detrital food cycle. Wagg et al. (2014) showed that soil biodiversity loss and simplification of soil community composition reduced plant diversity, decomposition, nutrient retention and nutrient cycling.

Saprophytic soil flora is the primary consumer in the detritus food web. They act on the organic wastes and convert them either into useful or into innocuous and less harmful substance significant in maintaining soil fertility, ecosystem functions and production. The distribution, abundance and activity of soil microflora are governed by soil fauna (Fig. 26.6).

Microarthropods provide supporting ecosystem services like nutrient cycling, soil formation and primary production (Hunt and Wall 2002). Their specific role in the primary productivity can be categorized into (1) facilitating nutrient acquisition by the vegetation through the mycorrhiza and N-fixing organisms; (2) regulating the flow of nutrients through decomposition, mineralization and immobilization; (3) mediating the breakdown of organic matter; (4) modification of soil structure which influences water availability to the plants; and (5) modifying the plant health by parasitism and pathogenicity (Swift et al. 1979; Lussenhop 1992). It is reported that in the presence of microarthropod fauna, the mass loss and mineralization of detritus are enhanced by about 23% (Seastedt 1984).

In saprophytic sequence, six mechanisms of interaction are important. Most of the mechanisms control fungal distribution and abundance by selective grazing of fungi. This periodic grazing induces compensatory fungal growth and releases over grown fungi population from competitive stasis. Micro- and mesofauna carry fungal propagules including root pathogens to root surface and dispersing fungal inoculums to newer places. The other mechanisms stimulate microbial activity through direct supply of mineral nutrients in the form of urine and faeces and stimulating bacterial activity by faunal movements and feeding activities.

Soil organisms can also be used to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes. This action is known as bioremediation. Many soil organisms can be detrimental to plant growth, for example, the build-up of nematodes and certain pests under particular

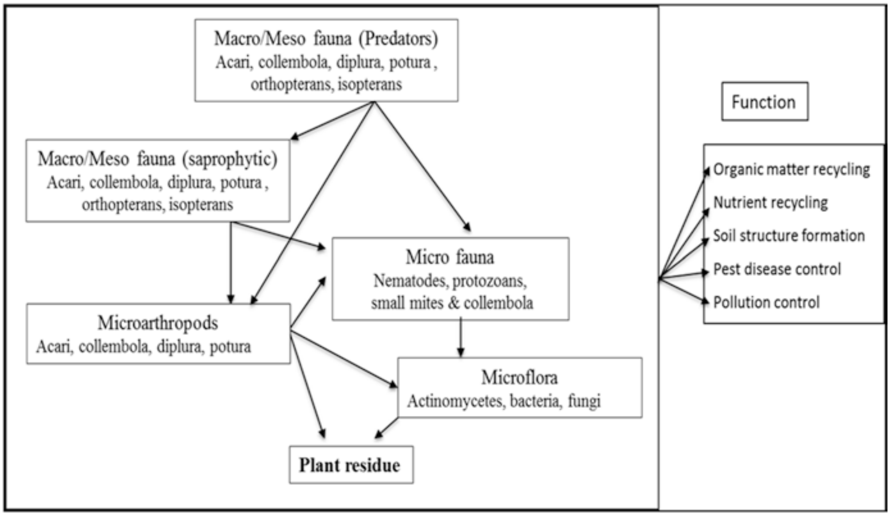

Fig. 26.6 Microarthropods in soil food web and their functions

cropping systems. However, they can also protect crops from pest and disease outbreaks through biological control and reduced susceptibility.

5 Microarthropods Associated with Grassland/Agroforestry Systems

Grasslands and agroforestry systems are perennial in nature. The soils of grassland systems, whether natural or the managed one, have abundant and diverse microarthropod fauna. The botanical diversity and management practices followed in these systems have influence on soil biota interactions (Barrios et al. 2012). The grassland systems are often put to agriculture use for desired productivity. But these conversions have been reported a negative effect on faunal diversity (Peterson and Krogh 1987; Larink 1997; Postma-Blaauw et al. 2010; Gagnarli et al. 2015). In agroforestry, there are aboveground interactions of trees and crops/grasses with or without livestock. On account of the perennial components, they have emerged as a sustainable alternative to agricultural production systems by providing environmental benefits such as biodiversity conservation, enhanced carbon sequestration and improved water quality (Barrios et al. 2012). In many cases, the reported soil mesofaunal density and richness of these systems are like the natural forest (Moco et al. 2009). In general, it can be stated that the plant diversity, land use, climate and management are the main factors that influence the soil microarthropods diversity and dynamics in the grassland and agroforestry ecosystems.

5.1 *Influence of Climate and Soil*

Climate exerts influence on abundance of fauna by directly influencing their biology and life processes or indirectly by altering their habitat and food availability. Life cycle extension of Antarctica mites (Booth and Usher 1986) or diapause during summer drought by *Sminthurus viridis* in Australia (Davidson 1933) are common among microarthropods. Seasonal fluctuation in abundance and vertical migration is a predominant feature of the population. Under favourable climate, they multiply or migrate to upper soil layers (Choi et al. 2003; Palacios-Vargas and Castano-Meneses 2003; Donghui et al. 2006; Rocheforta et al. 2006). Abundance and diversity of collembolan and mites are reported from perennial systems in monsoon season (Roy et al. 1998; Tripathi et al. 2007; Lakshmi and Joseph 2016).

Soil organic matter influences water holding and cation exchange capacity which in turn influence soil habitat and decomposer fauna. The soil most affecting soil attributes are moisture, temperature, organic matter, texture, porosity and pH. Larsen et al. (2004) found that soil compactness influence collembolan population. The reports from tropical soils suggest that organic matter and soil acidity affect soil biota differently in different land use systems (Geissen et al. 2007). Salamon and Alphei (2009) reported that soil pH is an important structuring force for Collembola communities in forests of Central Europe. The temperature and soil moisture are the main factors that influence seasonal abundance of collembolan and mites in grassland (Cole et al. 2005; Roy and Roy 2006). In fact, soil moisture has a very high influence on the reproduction and locomotion of microarthropods (Sjursen and Holmstrup 2004; Tsiafoulia et al. 2005; Moron-Rios et al. 2010).

Climate change is now considered as a major global threat. Enhanced CO_2 concentration is the reason for increase in atmospheric temperature and modification in precipitation pattern (IPCC 2007). The climate warming and precipitation modification directly influence soil temperature and moisture. The warming of soil may affect plant growth, vegetation composition, seasonality and phenology which influence the availability of organic matter inputs (Kardol et al. 2010). This modification affects the composition of rhizosphere micro-organisms and alters the microarthropods community occupying higher trophic level of food web (Kardol et al. 2011; Ostle and Ward 2012). The degree of these kind of changes may vary with the ecosystems and may have additive or antagonistic impact (Mikkelsen et al. 2008; Ostle et al. 2009).

The impact of climate change may be reduced to some extent by modifying the agroecosystems. The grassland, in general, has the capacity to neutralize the effect of warming and moisture conditions (Fenner et al. 2007; Wan et al. 2007). This is also indicated in an experiment on silvopasture systems exposed to enhanced CO_2 conditions in semiarid Central India (Bhatt et al. 2010). The results showed that *Panicum maximum* grass species was capable of higher carbon sequestration, while silvopasture systems (*Panicum maximum* + *Stylosanthes hamata* + *Leucaena leucocephala/Grewia optiva*) supported higher soil microarthropods populations as well (Table 26.2).

Table 26.2 Trend of microflora population and carbon sequestration in selected land use systems in Central India

	Microflora population (10^5 cfu g^{-1})			Microfauna population (10^2 m^{-2})					
Systems	Fu	Am	Ba	Mt	Cl	Nm	CSV (mgC ha^{-1})	CSS (mgC ha^{-1})	TCS (mgC ha^{-1})
Pm	6.73	75.40	47.93	48.86	40.72	1994	6.59	3.61	10.20
Cc	5.13	87.53	38.47	44.45	29.52	1819	4.27	1.13	5.40
Sh	5.00	99.40	74.67	60.74	21.72	1628	2.93	3.38	6.31
Pm + Sh + Ll	7.87	92.20	66.20	63.79	23.41	1896	8.63	2.70	11.33
Pm + Sh + Go	6.20	111.3	71.93	54.63	44.45	2047	8.48	2.93	11.41
Cc + Sh + Ds	2.87	95.93	46.80	82.80	26.81	1711	5.70	2.26	7.96
Cc + Sh + At	4.47	95.93	38.13	59.72	34.95	1839	6.68	2.03	8.71
Cd (5%)	1.74	37.87	29.76	17.15	10.34	106.4	–	–	–

Am Actinomycetes, *Ba* Bacteria, *Fu* Fungi, *Cl* Collembola, *Mt.* Mites, *Nm* Nematode, *CSV* Carbon sequestration in vegetation, *CSS* Carbon sequestration in soil, *TCS* Total carbon sequestration, *Pm Panicum maximum*, *Cc Cenchrus ciliaris*, *Sh Stylosanthes hamata*, *Ll Leucaena leucocephala*, *Ds Dalbergia sissoo*, *At Acacia tortilis*, *Go Grewia optiva*

5.2 Land Use and Vegetation Diversity

The botanical composition has been projected as major determinants of soil food web structure in different land uses (Bardgett et al. 2005). The plant diversity influences the habitat for the organisms as the extent of resource depletion by various plants decide the quality and quantity of litter and nutrients availability to the soil organisms (Wardle 2002). Sousa et al. (2006) in their study on the effect of land use intensity observed that Collembola react to the landscape richness. The number of species was more in natural forest and mixed-used landscapes than agricultural landscape. Several studies have documented the effects of different soil and litter attributes and land use practices on the colonization and activity of soil fauna (Aquino et al. 2008; Yang and Chen 2009).

A large pool of labile organic matter and microclimate due to permanent vegetation cover of grasslands provide favourable environment (temperature, moisture and nutrient diversity) for the soil biota, which in turn substantially contribute to soil organic matter turnover and nutrient dynamics for better production (van Eekeren et al. 2007). Possibly, inclusion of legumes in managed grasslands can promote C and N storage which influence soil microbial biomass for supporting biodiversity at higher trophic levels of food web (De Deyn et al. 2009). In seminatural grasslands where C and N tend to be low in soil, food webs were found to be dominated by fungi and microarthropods (Rutgers et al. 2008). Higher plant diversity in grasslands supports rich soil faunal diversity at all trophic levels (Proulx et al. 2010). However, at higher trophic levels, these effects are less pronounced (Scherber et al. 2010).

Plant diversification in agroforestry and forest systems provides a diversity of microhabitats, contributing to a larger soil biological density and diversity (Richter et al. 2007; Laossi et al. 2008). Bano (2006) reported that even in early establishment phase, multispecies silvopasture system and intensively managed cultivated pastures supported species diversity similar to that of natural systems in Central Indian semiarid region (Table 26.3). Promotion of silvopastoral systems on degraded grasslands in Central India has increased microarthropod diversity. However, botanical composition of the systems had influence on diversity of microarthropods (Table 26.4). The productivity was also found (Table 26.5) related to soil biota abundance (Roy et al. 2008).

5.3 Role of Management Practices

Introduction of legumes, fertilizer/manure application and grazing are the common management practices that affect both the abundance and diversity of soil icroarthropod communities. In Central New York (USA), land use under a gradient of management intensity from corn fields, herbaceous old fields, and shrubby old fields to hard wood forest, was identified to be a significant factor that influenced oribatid mite diversity within individual soil cores and at the site scale (Minor and Cianciolo 2007). The low-input systems with a more heterogeneous habitat and

Table 26.3 Microarthropods diversity in different land uses

Soil biota	Number of species					
	Bare	Grass	Past[a]	Tree	Silvo[b]	Agri
Collembola	6	14	13	14	13	8
Cryptostigmata	4	32	31	28	27	10
Prostigmata	4	7	7	7	7	5
Mesostigmata	3	14	16	13	12	1
Astigmata	–	3	3	3	3	1
Other arthropods	36	44	38	37	48	41

Bare Barren land having seasonal vegetation for short period of about 45 days, *Grass* Natural grassland dominated by *Cenchrus ciliaris*, *Heteropogon contortus* and *Panicum maximum*, *Past* Cultivated pasture land where grass is harvested annually for silage/hay making, *Tree* 35-year-old *Albizia amara* plantation, *Silvo* Multispecies silvopasture system consist of *Azadirachta indica*, *Acacia nilotica*, *Leucaena leucocephala*, *Ziziphus mauritiana* and *Dalbergia sissoo* along with three grass species and legume *Stylosanthes hamata*, *Agri* Cowpea-maize cultivation followed by lucerne

[a] Data was collected at third year of establishment

[b] Data was collected at fifth year of establishment

Table 26.4 Plant and soil biota diversity of soil biota in different silvopasture systems

Soil biota	Silvopasture systems			
	SL-1	SL-2	SL-3	SL-4
Collembola	10	9	7	13
Cryptostigmata	20	13	19	27
Prostigmata	5	5	3	7
Mesostigmata	5	9	9	12
Astigmata	1	1	–	3
Other arthropods	20	22	20	48

SL-1 *Acacia tortilis*, SL-2 *Albizia amara*, SL-3 *Hardwickia binata*, SL-4 Multispecies silvopasture

Table 26.5 Productivity of different land uses and associated soil biota

Soil biota (abundance)	Degraded land	Natural grassland	Managed pasture	Silvopasture
Actinomycetes (10^5 cfu g^{-1})	99.1	181.4	204.1	281.9
Bacteria (10^5 cfu g^{-1})	36.3	105.9	133.1	114.3
Fungi (10^5 cfu g^{-1})	6.81	11.0	10.4	19.8
Azotobacter (10^4 cfu g^{-1})	3.5	–	–	10.2
Microfauna (10^4 m^{-2})	8.6	42.8	39.3	36.8
Mesofauna(10^4 m^{-2})	2.1	20.3	14.9	19.3
Macrofauna (m^{-2})	29.1	52.2	41.1	59.9
Productivity (mg ha^{-1})	0.01–0.10	0.10–1.50	2.10–5.80	3.00–7.80

Table 26.6 Soil arthropods recorded in *Lasiurus sindicus* (LS) based grassland under different management practices in Thar Desert of India

	Soil chemical parameters (ppm)							Arthropods (no.)	
Land uses	SOC	MBC	FDA	DHA	NH_4^+-N	NO_3^--N	LC	Micro	Macro
SP	1139	29.07	3.34	31.45	5.25	4.69	214.97	140.6	45.4
MG	947	24.91	3.04	25.38	5.03	3.68	172.33	89.8	64.0
UMG	918	23.87	3.12	27.55	4.55	4.56	177.16	143.3	48.2
G-cg-C	991	25.31	3.29	31.09	5.46	4.45	186.71	57.4	102.2
G-cg-S	1077	23.7	2.87	24.24	5.17	4.96	175.67	84.8	34.4
G-OG	968	22.01	2.99	27.47	5.22	5.06	147.16	30.9	21.9

UMG Fenced natural grassland, grazing not allowed, *SP* Silvopasture (LS + mopane), grasses harvested annually; *G-CG-C* Grassland under moderate cattle grazing, *G-CG-S* Grassland under moderate sheep grazing, *G-OG* Grassland under heavy mixed herd grazing, *MG* High-input grassland maintained for seed production, grasses harvested annually

resource contain a more diverse fauna, characterized by species that are more persistent (Wardle et al. 2004; Roy et al. 2010).

Grazing and its management are extensively practiced in grasslands and pastures for livestock. Reduction in vegetation composition and amount of surface litter alters the soil microclimate that results in decline of mesofaunal density in sheep-grazed pasture (King and Hutchinson 1976). The selective grazing by cattle in respect to age of the plants and plant species altered the vegetation structure and reduced the height of tall grasses requisite to build webs by linyphiid spiders responsible for decline of the spider community (Harwood et al. 2003). Significant reduction in dominant microarthropod abundance and diversity has been reported due to cattle grazing (Clapperton et al. 2002; Battigelli et al. 2003). The grazing can influence microarthropod community structure by altering botanical composition of land by direct addition of organic matter through faeces and urine and disruption through defoliation and trampling (Helden et al. 2010). However, there are reports of moderate early season cattle grazing on increased total invertebrate abundance by 71% in a period of 4 years. The most responsive groups are Araneae and Collembola (Eschen et al. 2012). In the Indian Thar Desert, *Lasiurus sindicus* grasslands under different grazing management practices were evaluated for some soil parameters and microarthropod fauna. Highest faunal build-up was recorded under controlled grazing condition either by small ruminants or cattle (Table 26.6). The microarthropods build-up was synchronized with labile carbon and soil enzyme activity (Roy and Panwar 2014).

The conversion of grasslands and forestry ecosystems to agriculture has been occurring from centuries. This is one of the main causes of substantial loss in biodiversity and often irreversible negative loss on soil fertility. The agricultural management operations like tillage (Schmidt et al. 2003; Van Eekeren et al. 2008), fertilizer/manure application (Arroyo et al. 2003; Badejo et al. 2004; Roy et al. 2012), pesticide application (Roy et al. 2004, 2009) and reduced crop diversity (Wardle et al. 2003; St John et al. 2006) negatively affected mesofauna diversity and abundance in comparison with the natural landscape. Irrigation pattern too has an impact on soil collembolan and mites in a complex and non-linear way as it modifies soil moisture regime and is dependent on the soil type. The collembolan community have shown higher species evenness and diversity in the frequently irrigated plots, while the same was observed in the infrequently irrigated plots in case of oribatid mite community (Tsiafoulia et al. 2005). Studies also indicated that loss of soil biota to agricultural intensification is relative to the size of the organism (Postma-Blaauw et al. 2010).

6 Conclusions

The tiny fraction of soil that is alive, organized and interactive plays a key role in delivery of a range of ecosystem services. The soil and their biodiversity support various agricultural, forestry and allied systems. The management practices in grassland and agroforestry systems have impacts on soil biota at different temporal and spatial scales. The functional relationship between management intensity and their implications on soil biota are complex and, therefore, have varied effects that are sometimes conflicting on ecosystem services. Legume introduction in the system may potentially reduce the productivity of sward but promote ecosystem services in form of soil structure, water retention, biodiversity, carbon and nitrogen content. Therefore, trade-offs are required. Promoting well-designed agroforestry systems may be a good strategy over agricultural systems in view of meeting the challenges of optimizing crop productivity while maintaining provisions for ecosystem services. The sufficient organic inputs of different kinds from agroforestry are able to preserve soil cover besides increasing the diversity and persistence of active soil biota. However, in-depth understanding about tree-soil biota interactions is still poor, more so in tropical systems on account of limited publications with quantitative field data. Considerable emphasis on this subject through evolving a standard methodology for grassland and agroforestry systems and a mechanism of periodical assessments is required in future. The microarthropod communities may be promoted as quick tool to assess soil quality and biodiversity (Parisi et al. 2005). This will lead to design of superior systems that enhance complementarities, facilitation and synergies in tree-soil biota interactions for sustained provisioning. Strategic use of modern techniques like molecular and spectroscopic tools may refine the studies and characterize hotspots of biological activity.

7 Future Thrusts

- Developing a common methodology for sampling and characterization of soil biota that allows better comparisons among grassland and agroforestry systems across the region.

- Identifying and characterizing hotspots of biological activity through strategic use of molecular tools, analysis of stable isotopes and using spectroscopic techniques.
- Establishing linkages between key soil biota and ecosystem functions at different temporal and spatial scales.
- Optimizing plant-soil biota interactions that improve agroecosystem function and soil health.
- In context of the land use changes and the climate change scenarios, interactions between plant community function and diversity and activity of soil communities and their role on carbon cycling require in-depth study.
- Developing local soil health monitoring systems that generate valuable information to convince the owners of the land about capacity of their land in providing ecosystem services.
- Linking of local level soil health monitoring system to economic services.
- Developing standard methodology for payments of ecosystem services and rewarding the community following good management practices.

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Chapter 27
Role of Entomology in Sustaining Agroforestry Productivity

Sharmila Roy, M. M. Roy, Pradeep Saxena, and Ruquaeya Bano

Abstract A variety of insects are associated with various stages of their growth with agroforestry systems. Earlier, in agroforestry studies relative emphasis on the insect-pest component was low because of other priorities. Now, there is an increased realization and awareness about the emergence of serious pest problems in promising agroforestry systems and other associated risks. In agroforestry systems, to enhance productivity and diverse uses, it has become a practice to introduce trees and other plants from different regions. Another likely point in context of agroforestry systems is increase in population and diversity of beneficial insects like pollinators, predators, and soil arthropods which sometimes may reduce pest loads. Many interactive factors operate in agroforestry systems like shaded conditions, barriers in insect movement, natural enemies, host plant resistance, etc., and they influence intensity of damage. Even the masking effect of odors released by different plant species in such systems interferes with insects' orientation abilities. The concept of biological control is considered appropriate in context of agroforestry systems that prevent high pest build and favor natural enemies. More investments in understanding of key target pests in agroforestry and their interactions will be useful in refining existing systems and designing new systems from the viewpoints of productivity as well as sustainability.

Keywords Biological control · Crop geometry · Diversity and dynamics · Pollinators · Trophic interactions

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1 Introduction

Entomology is the scientific study of insects. The insects are a predominant group of herbivores, and they have developed a variety of associations with plants over millions of years of coevolution. The classification of an insect as pest is a subjective one, based on its potential to its damaging effect. There are several insects that can have damaging or killing effect on agricultural crops, trees, shrubs, etc. Sometimes this damage may be on an economical scale and, therefore, considered pests. There may be damaging effects on harvested food or agricultural animals as well (ISPM 2006).

Agroforestry systems are sustainable land-use systems, which combine agricultural and forestry systems and technologies to create more diverse, productive, healthy, and ecologically sound systems (Jose 2009). The output of any production system can be enhanced either by an increase in production level or by a reduction in the losses from it. In agroforestry systems, prevention of losses of all kinds is a strategy to achieve higher output without compromising its sustainability. The components of agroforestry are mainly responsible for the diversity and dynamics of insect fauna. The management of insect pests in agroforestry systems is considered crucial to sustained production. As early as in the 1990s, ICRAF strategy mentioned pest management as a research priority area (ICRAF 1990). The farmers have recognized this as an important issue for agroforestry research (Prinsley 1991).

Insect-pest regulation in agroforestry is a function of interactions among the different components of the system. Diversity of plant material in polycultural systems often leads to lower pest intensities, while taxonomically related plant species tend to share common pests. Generally, polyphagous pests inflict greater injury to plants in a mixed vegetation system when compared with monophagous insect pests. Andow (1991) reported that monophagous herbivores are more likely to decrease in diverse systems than polyphagous pests (61.3% versus 27.1%) and less likely to increase (10% versus 43.8%). Similarly, strata difference due to trees may act as physical barriers to movement of insects within the field. Such a barrier effect may also result from the presence of nonhost plants among the host plants (Rämert et al. 2002; Letourneau et al. 2011). The host range of insects may be altered due to the masking effect of odors released by different plant species that interfere with orientation abilities (Tang et al. 2013).

It is considered that at present, the information available about insect pests and their management in different agroforestry systems needs to be updated with renewed emphasis in a system context. This paper is an attempt to understand insect-pest issues in agroforestry systems and suggest strategies to cope with them, mainly in the context of tropics.

2 Agroforest Entomology

The impacts of insects in traditional agroforestry systems or practices were largely ignored especially in the context of pest biology and ecology. However, in later years when agroforestry emerged as a full-fledged discipline, it was realized that in-depth understanding of pest biology and ecology and the associated biodiversity is important in the farm area. Also, related observations from outside the farm area are very pertinent.

The insect-pest problem of agriculture crops and the problems due to introduction of woody perennials create different dimensions to the entomology features of agroforestry. The amalgamation of tress that matures with the time and the crop that is annual in nature makes the environment complex for its insect habitants. The complex biological interaction due to taxonomical relatedness or diverse botanical composition of the system, introduction of exotic species, etc. may influence insect community. Because of this, Epila (1986) suggested that information of insect ecology is required in terms of (i) plant species diversity, (ii) perennial woody plants, (iii) age of the agroforestry system, and (iv) crop and relatedness of companion crops. This information may be useful for establishment and maintenance of productive agroforestry system.

3 Ecological Interactions

In natural system plant communities developing through natural selection have a degree of inbuilt resistance to insect attack. In contrast agroforestry introduces plant diversity in a land unit with the preferred attributes to achieve essential productivity. Interactions among the components of the agroforestry system can be positive, negative, or neutral and so their impact on insects. To some extent the nature of pests is also important. There are possibilities that polyphagous pests feed on taxonomically diverse plant species, monophagous multiply in monocrops, or the host range of insects varies based on their development stages like chaffer beetle's grubs feed on crops, while adults prefer woody component of agroforestry systems (Rao et al. 2000).

The suitable habitat, food, and climate are responsible for buildup of insect fauna in any ecosystem. The diversity and dynamics of pests are greatly influenced by the tri-trophic interaction of vegetation, insects, and their predators (Fig. 27.1). The plants (producers), including the trees, crops, and weeds, create first trophic level, may be attacked by a wide range of herbivores (primary consumers), and form second trophic level. Herbivorous species in turn are attacked by natural enemies (secondary consumers), constitute third trophic level. Natural enemies include predatory arthropods (insects, predaceous mites, spiders, scorpions, centipedes, etc.), vertebrates (insectivorous birds, mammals etc.), and parasites and pathogens (nematodes, insect parasitoids, bacteria, viruses, fungi, protozoa) which play a significant

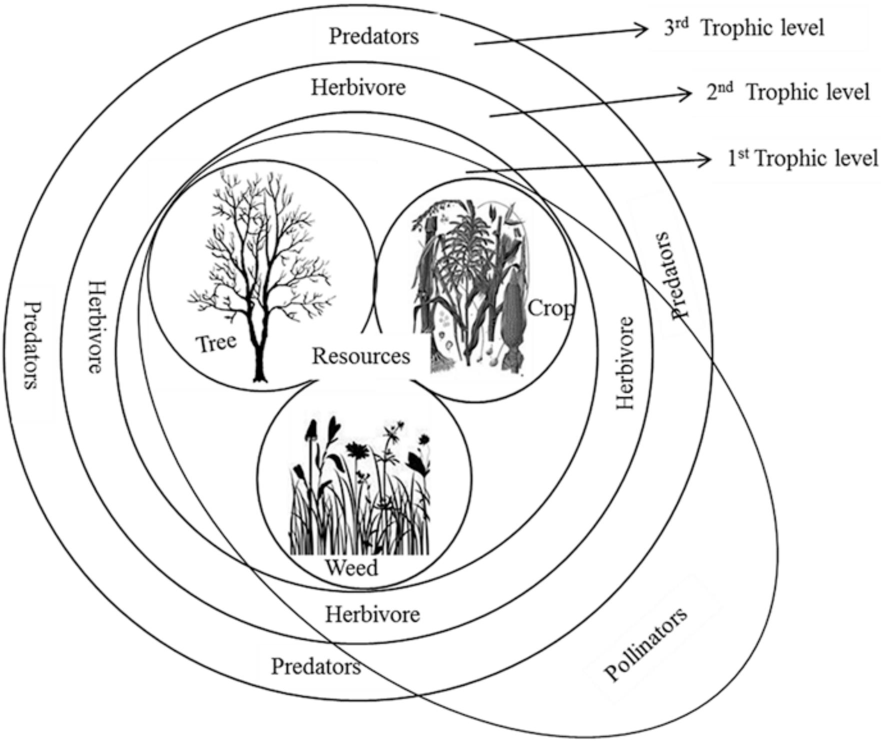

Fig. 27.1 Trophic interaction in agroforestry systems

role in the population dynamics of pests of agroforestry (Sileshi et al. 2001, 2008). The complementary ecosystem services, i.e., pollination and natural pest control contribute significantly to crop productivity in agroforestry systems (Lundin et al. 2012).

4 Status of Insect Pest

Agroforestry introduces plant diversity in a land unit, over both time and space, and this is supposed to reduce pest in the system. But this may not always result in desired pest populations' reduction. It may be pest specific, site specific, or affected by other abiotic factors. Some crop pests find refuges in adjoining woodlands, hedgerows, and forests; when environmental conditions in the fields become favorable, they invade production systems. Some insects like aphids can complete one to several generations on alternate wild host plants before migrating onto crops. Similarly, bruchids are seed pests of grain legumes and are observed feeding on seeds of wild leguminous woody plants. Incorporation of wild flowering plants into agricultural systems or conserving such plants in the hedgerows serve as a source of nectar and pollen, which enhances the effectiveness of parasitoids and pollinators. The woody perennials act as physical barriers may reduce the dispersal and searching ability of pests/parasites (Grout and Stephen 1995). Some plants mask the volatile signals arising from food plants and may confuse the pests which depend on these volatile cues to locate their hosts (Bhatt et al. 1997; Zaka et al. 2010). Indigenous and exotic leguminous trees planted for soil fertility replenishment in East and Southern Africa have been found to harbor many herbivorous insects, indicating that widespread adoption of fallow systems may aggravate insect pests (Girma et al. 2006). The change in microclimate because of agroforestry adoption is also likely to influence insect-pest activity within the system (Sileshi et al. 2008).

There are several experimental evidences of insect incidences from various systems showing positive and negative interaction with the systems and their productivity (Rachie 1983; Klein et al. 2002b; Landis et al. 2000; Sperber et al. 2004; Philpott and Armbrecht 2006; Lalnunsangi et al. 2014; Novais et al. 2016a, b). In this section, we summarize the information available on insect pests relevant to the mechanisms behind the effects of tree crop combinations on insects (Table 27.1). Such information may be effectively used in suggesting successful combinations of agroforestry systems.

5 Designing Systems for Regulating Insect Pests

The biodiversity components of agroforestry play an important role in functioning of the ecosystem. There are two ways of looking at biodiversity in agroforestry systems. Firstly, it is inherent in the design, that is, inclusion of trees, crops, livestock, etc. by the farmers. Secondly, the associated biodiversity includes insect pests and their natural enemies that colonize the agroecosystems and thirdly the insects inhabiting outside the systems. The agroforestry ecosystems may be classified into three biotic components: the productive biota, which is mainly responsible for provisioning services; which contributes to productivity through pollination, biological control, etc. the resource biota e.g., the wasps may visit nectar in trees' flower and may act as natural parasitoids of crop pests. The third component is destructive biota, i.e., pest component to which farmers aim at reducing their impact through management (Swift and Anderson 1993). All these factors are intricately related and performing various ecosystem functions (Fig. 27.2).

Agroforestry systems, particularly the multifaceted ones, have a great potential for controlling pest populations through increasing the efficiency of biological control agents. It has been demonstrated through trials that the biodiversity may be utilized for effective pest management in agroecosystems (Andow 1991; Roy 1994; Altieri and Nicholls 2004). It is also possible to stabilize select insect communities that support populations of natural enemies or have deterrent effects on herbivores by designing agroforestry systems with desired vegetation components (Gurr et al. 2004).

Table 27.1 Insect pests associated with some agroforestry systems

S. No.	Agroforestry systems	Factors	Mechanism	References
1	Cocoa + *Leucaena*	Polyphagous pest	More attacks of defoliating Lepidoptera	Room and Smith (1975)
	Cocoa + coconut	Taxonomically different plant	Less as coconut is not a host	
2	*Acacia* + pea	Taxonomically similar tree and crop combined	Accentuated *Etiella zinckenella*	Szeoke and Takacs (1984)
	Legume trees + groundnut		Beetles *Caryedon serratus* infest seeds of both the components	
3	*Eucalyptus* + tea	Vegetation combination	Attack by *Chrysolampra flavipes* increased	Gope (1985)
4	*Acacia* + *Eucalyptus*	Introduction of exotic plant species	*Celosterna scabrator*, a minor pest of *Acacia* spp., attacked eucalypts over time in India	Sivaramakrishanan (1986)
5	Pond cypress + rice/wheat + fish	Diverse components	Low plant hopper population	Shi and Gao (1986)
	Rice	Monoculture	High plant hopper population	
6	Black gram + sorghum/pigeon pea	Crop combination	Reduction in pest numbers and increase in predators	Dhuri et al. (1986)
	Green gram + sorghum/pigeon pea		Increase in pest numbers	
7	*Eucalyptus* + cassava combination	Tree-crop combination	Mite populations on cassava increased	Ghosh et al. (1986)
	Banana + cassava combination		Mite populations on cassava decreased	
	Leucaena + cassava		*Retithrips syriacus* on *Leucaena*	
8	Cassia + mixed cropping	Plant diversity	*Trachylepis* sp. higher on cassia	Bhatta and Bhatnagar (1986)
	Cassia fistula		*Trachylepis* sp. low	
9	*Leucaena* + lettuce, tomato, cabbage	Tree-crop combination	*Frankliniella occidentalis* infestation to *Leucaena*	Yudin et al. (1986)

10	Coffee + eucalyptus	Tree-crop combination	*Oiketicus kirbyi*, a pest of coffee, develops on eucalyptus	Arce et al. (1987)
11	Neem (*Azadirachta indica*) + pearl millet and sorghum	Tree-crop combination	The grasshopper population was lower	Amatobi et al. (1988)
	Acacia nilotica + pearl millet and sorghum		The grasshopper population was higher	
12	Collards + beans /or allowing weeds to grow	Crop combination	Decreased flea beetle	Altieri et al. (1990)
	Beans + grasses		Population of *Empoasca krameri* was reduced	Altieri et al. (1977)
13	*Leucaena* + rice/cassava/green bean	Scattered and low density of trees	Low psyllid population	Parera (1988)
	Leucaena	Monoculture induce high food availability	High	
14	Bamboo + rape	Crop diversity	Low-scale insect due to more coccinellids (rape plant aphids served as host for the predator	Xu and Wu (1989)
	Bamboo	Monocrop	High scale insect	
15	Oil palm + *Leucaena/Albizia/Ailanthus/ Casuarina*	Crop diversity	Low pest population	Dhileepan (1991)
	Oil palm + cocoa		High pest, common pests	
16	*Sesbania* plantation in fallows in East and Southern Africa	Intensive use of one species	Severe defoliation by *Mesoplatys ochroptera* beetles	Steinmuller (1995) and Sileshi et al. (2000)
		Minor pests take up epidemic proportion		
17	Coffee- and cocoa-based agroforestry	Crop geometry	Increased predators and pollinators	Klein et al. (2002a, b)
18	*Alnus*-based alley cropping	Pest susceptible crop for the region	High pest population	Nyeko et al. (2002)

(continued)

Table 27.1 (continued)

S. No.	Agroforestry systems	Factors	Mechanism	References
19	Albida + rice	Crop combination	Low infestation of major rice insects	Islam et al. (2006)
	Akashmoni + rice; Jhau-rice	Crop combination	High infestation	
	Rice	Monocrop	Low infestation	
20	Cocoa + agriculture crops		Low pests of cocoa due to high population predators	Bisseleua et al. (2013)
21	Mixed apple and timber trees + crop	Crop geometry	Reduced damage by scab and low insect-pest population in apple	Smith et al. (2014)
22	Traditional agroforestry	Crop geometry	High predator population	Lalnunsangi et al. (2014)
	Teak (*Tectona grandis*), tung (*Aleurites fordii*) and *Leucaena* with maize (*Zea mays*), *Phaseolus vulgaris*, and/or *Vigna sinensis*			
23	Traditional cocoa agroforestry	High diversity of bark beetles and the favorable abiotic conditions, whereas the low abundance of prey in the native forest	High predator beetle diversity and abundance	Novais et al. (2016a, b)
	Cocoa + rubber tree	Severe abiotic conditions in the rubber agroforest	Low predator population	
24	*Leucaena*	Accidental entry of exotic pests	Severe attack of *Heteropsylla cubana*	Rao (1995)
	Cupressus and *Juniperus*	Exotic pests attack susceptible local trees	Aphid *Cinara cupressi* devastation	Murphy (1998)
	Neem	Their natural enemies not available or established	Severe damage by yellow scale	
	Samanea saman		Damage by *Leucaena psyllid*	Braza (1987)
	Fruit trees of West Africa		*Rastrococcus invadens* attack	Agounke et al. (1988)

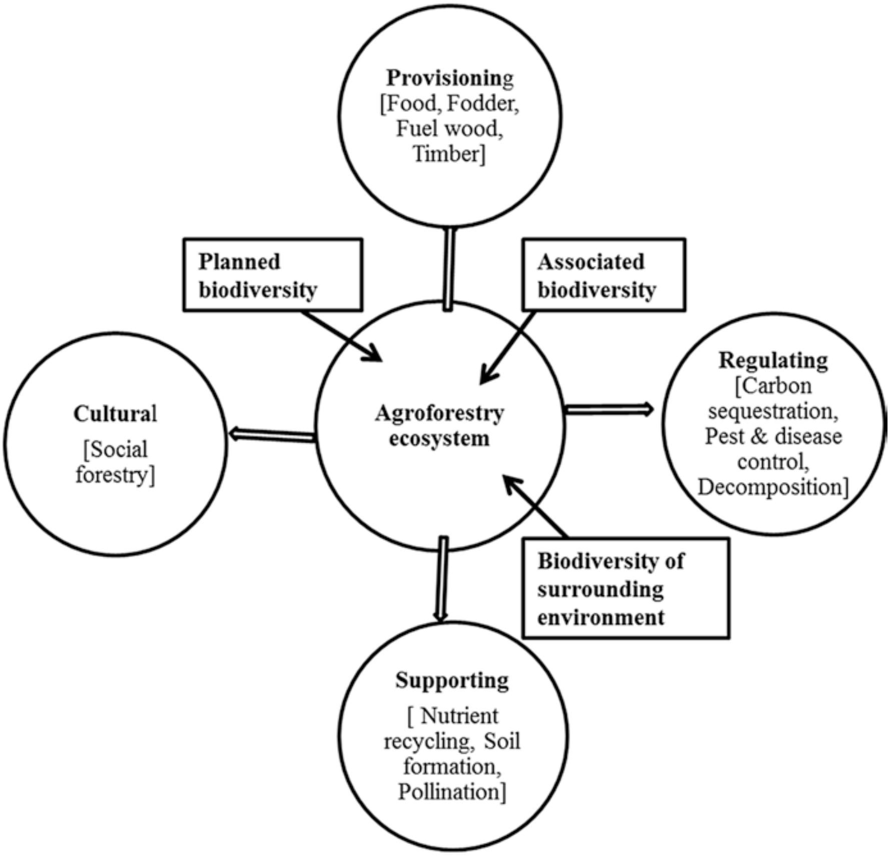

Fig. 27.2 Intricate relationships between plant-insect biodiversity and agroforestry functions

Agroforestry systems of the hilly regions of the Northeast India are one of the excellent examples of maintaining low herbivores population through rich natural enemy population in the systems. The presence of the fringe area of natural undisturbed vegetation and the untilled area around the trees provided undisturbed habitable conditions for predatory fauna. These systems are maintained in small scale, and the land use evolved through conventional information that require low external inputs like fertilizers, pesticides water, etc. (Lalnunsangi et al. 2014).

The farmers of Cerrado biome in Brazil selected species as well as the design for the agroforestry systems. They included native non-crop species, fruit trees, and crop species based on personal experience for marketable crops and species for multiples usages, such as timber extraction, medicine, and own use preference. Adaption to soil and climate conditions in the region was considered in addition. Establishment of rows of agroforestry systems nearby and surrounding vegetable crop plots as hedgerows enhanced the diversity of herbivores and natural enemies in vegetable production farms. Integrating of agroforestry systems to vegetable crop

Table 27.2 Some useful conclusions based on in-depth observations in context of insect-pest management of agroforestry systems

Interactions	Effects
Tree in fallow or boundary planting harboring insects	May increase pests damage
	May increase predators and pollinators population
Trees serving as alternative hosts to insect pests and disease vectors	Increased pest damage on crops
Tree and crop belong to similar taxonomic groups sharing the same pest	Increase in pest problems
Trees dominating crops by competition for resources	Reduced crop vigor may induce susceptibility to pests attack
Trees serving as refuge and food source for natural enemies	Reduction of pest problems in crop
Trees limit movement and life cycle of insects	Reduction in insect population
Trees lines act as mechanical barriers for the spread insect pests, vectors, and pathogens	Reduction of pest colonization
Increases the pool of available soil nutrients, especially N	Increased crop vigor to withstand some pests
	Increased vigor inducing susceptibility to other pests
Trees improving microclimate in harsh environments	Buildup of pests and pathogens
Tree litter and mulches increasing soil humidity and lowers soil temperature	Increase in soil borne insects
Weed use nutrients	Reduced crop vigor may induce susceptibility to pest's attack
Weeds serving as refuge and food source for pests and natural enemies	Reduction of pest problems in adjacent crop fields
	Increase in pest problems

plots also acts as barrier crops, windbreak, and for recovering natural areas in degradation process (Harterreiten-Souza et al. 2014).

Land use intensification does not always influence predator-prey and pollinator services. However, shifts in the composition of pollinator visitors in coffee plantation in Tanzania showed that wild pollinators can compensate declines of honeybees on coffee farms that are near to tropical forest fragments but not on isolated farms. Thus, optimization of productivity in agroforestry landscapes requires not only knowledge of multiple ecosystem services operating in parallel but also of management strategies that reliably match the demands of the wild animals providing these services (Classen et al. 2014). Table 27.2 lists some useful inferences based on behavioral pattern of insect pests that may be useful in managing insect fauna of agroforestry systems.

6 Conclusion

The management of insect pests is necessary for sustained production and viability of agroforestry systems. The interactions among various components of agroforestry like physical (shade, microclimate) and biological (plant-pest or plant disease) are complex. The biological interactions are much more complex compared to the physical ones, and they are too specific as well. In agroforestry, there is more possibility of arthropod diversity and less pest population when compared to agriculture or forestry systems. Appropriately designed agroforestry systems have significance in reducing crop stress and improving tolerance of crops against pests and diseases by influencing the conditions for pest and disease organisms and their natural enemies.

However, more regional specific work is required on the mechanisms that lead to better pest management under agroforestry. Basic research in understanding life histories of target insect pests may also generate valuable information in designing better agroforestry systems and practices.

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Chapter 28
Urban and Peri-urban Agroforestry as Multifunctional Land Use

S. Borelli, M. Conigliaro, S. Quaglia, and F. Salbitano

Abstract In this era of global changes, rapid urbanization rates, climate change impacts and growing socio-environmental concerns are negatively impacting on various aspects of urban life, such as human health and well-being, urban economy stability, biodiversity levels, land productivity and natural resources availability.

In this context, cities – having become the main centres of consumption and production worldwide – need to move towards more sustainable and resilient urban development models, considering novel approaches aimed at integrating grey and green infrastructure, economic growth and environmental concerns, knowledge diffusion and poverty and hunger eradication.

In this regard, the implementation of urban and peri-urban agroforestry (UPAF) systems – associated with the integration of urban food systems into urban planning – can greatly support the provision of ecosystem services to urban dwellers, thus contributing to the improvement of their livelihood through increased food and nutrition security, energy and fresh water availability, regulation of local climate, carbon sequestration, maintenance of genetic diversity, recreation opportunities and health improvement. In this sense, UPAF is emerging as a new urban practice addressed to promote sustainable land use as well as the integration between urban and rural development. However, its implementation in urban contexts presents several key challenges, such as land tenure conflicts, lack of integration with urban policies and plans and technical knowledge, as well as necessity of innovative governance models.

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In this context, the aim of this chapter is to outline, through a review of the relevant literature and case studies from both developed and developing countries, the benefits deriving from the implementation of UPAF systems and highlight how these practices can support the improvement of urban sustainability and resilience, particularly in terms of enhancement of provisioning, cultural, regulating and supporting ecosystem services.

Keywords Ecosystem services · Resilience · Sustainability · Urban agroforestry · Urban planning · Land tenure conflicts

1 Introduction

In the last decade, we have witnessed an *urban transition*[1]: according to UN statistics, in 2007 for the first time, the world's urban population exceeded the rural one (Fig. 28.1). This figure is expected to keep rising and will reach 66% by 2050

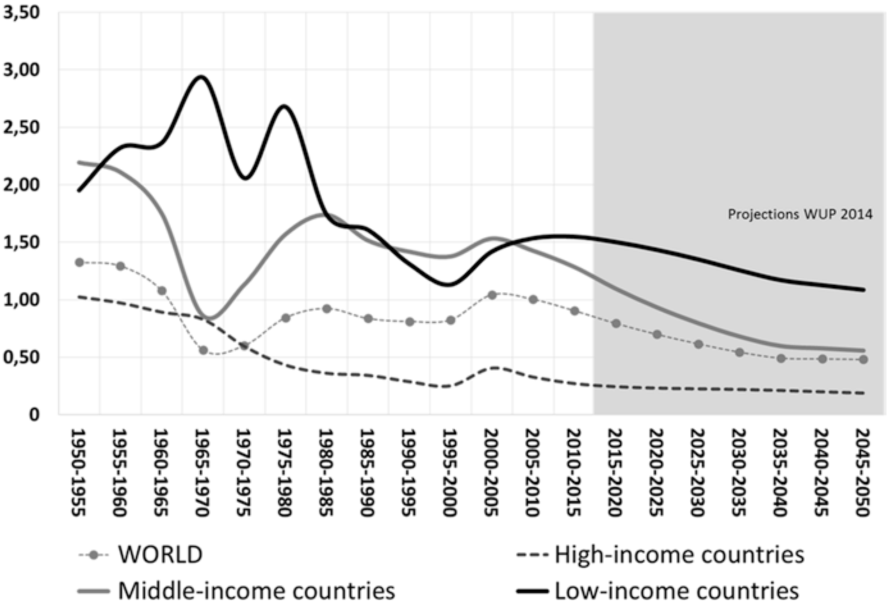

Fig. 28.1 Urbanization rate in development regions of the world (Source: United Nations, Department of Economic and Social Affairs, Population Division 2014)

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[1] Firebaugh G. (1979) defines the urban transition as: "*the reorganization of human society from being predominantly rural and agricultural to being predominantly urban and non-agricultural*".

(UN 2014). Even though urbanization is following different trends in the different regions, it must be considered and addressed as a global *phenomenon*.

In this context, rapid urbanization and ongoing global change – characterized by factors such as climate change, natural resource depletion, reliance on fossil fuels and pesticides, migration flows, volatile markets and growing wealth inequity – will contribute to a deepening food crisis and to an increase of inequality, poverty and dietary deficiency diseases in urban areas.

Even though cities cover less than 3% of world's surface, they consume 75% of world's natural resources. In fact, while they do offer many advantages to urban dwellers, by fragmenting and degrading natural habitat, reducing biodiversity, disrupting hydrological systems, altering energy flow and nutrient cycling, as well modifying people's lifestyles, they are also deeply altering the functioning of local and global ecosystems (Alberti 2005). These dynamics and the associated unsustainable land-use practices affect the provisioning of the key ecosystem services[2] on which urban dwellers' livelihood depends: good quality water provision, soil fertility conservation, food production, climate regulation, air quality increase and wood fuel and timber provision.

To address the above issues, cities are increasingly called to work on the development of sound strategies and policies aimed to enhance the multifunctionality of urban and peri-urban green and blue infrastructure (*sensu* Borelli et al. 2015), towards the recovery and maximization of the benefits they can provide for a more sustainable and resilient model of urban development. In light of the increasing loss of political power of national states due to the impact of globalization and decentralization of government worldwide, cities' role in managing those issues is expected to become more and more relevant in the upcoming future.

In this regard, urban food systems and practices such as urban and peri-urban agriculture, forestry and agroforestry are among the most prominent strategies – both in the Global North and South – to enhance food security and nutritional status (Clark and Nicholas 2013), protect and valorize natural capital and improve the sustainability and resilience of urban areas, contributing to fairer, healthier and more affordable urban food systems.

Especially at regional and local level, awareness regarding the importance of improving the urban food systems has only increased in the last decade. This change has been influenced by the *new food equation* (NFE) (Morgan 2009; Morgan and Sonnino 2010) that refers to various complex factors influencing the current food paradigm, such as the food crises of 2007–2008, the raise of food security and climate change as fundamental global concerns, the land-grabbing *phenomenon* in the developing world and the rapid expansion of urban areas. These factors have fostered the adoption, from local to national level, of novel approaches to the integration of food issues in the urban agenda, in both developed and developing economies, aiming to overcome the urban–rural dichotomy (Donadieu 2013), as demonstrated, for example, by the subscription in 2015 of the *Milan Urban Food Policy Pact*, an

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[2] Daily GC (1997) defines ecosystem services as:" the *conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life*".

international protocol engaging 133 cities worldwide in the development of more sustainable, inclusive and resilient urban food systems.

As a result, in recent years, an increasing number of cities has been promoting urban and peri-urban agriculture (UPA) and forestry (UPF) practices in a variety of spaces at different scales – plot, farm and landscape – through their integration into local, regional and also national policy, with the aim of tackling different urban challenges such as food security, poverty, mitigation of and adaptation to the effects of climate change and prevention of non-communicable diseases, such as obesity and malnutrition (Wiskerke 2015).

Currently, widespread UPA practices are found in many cities worldwide. For example, Amsterdam has devoted over 350 ha of land to urban gardens for the production of fresh food and other goods for urban population (van Leeuwen 2010), while in Dar es Salaam, Tanzania, 90% of leafy vegetables and 60% of milk consumed in the city are produced within or around the urban area (Lee-Smith and Prain 2006).

UPF also has the potential, through sound planning and management of urban forests and trees, to provide a variety of environmental, sociocultural and economic benefits to city residents. Urban and peri-urban forests can play a relevant role in meeting new urban demands, as demonstrated by their increasing integration into urban planning by local authorities, through the adoption of strategies and policies establishing long-term targets to mitigate climate change effects and reduce disaster risks (Konijnendijk 2003; Nowak and Dwyer 2007; Clark and Nicholas 2013). For example, in 2007 the Mayor of London launched a climate change adaptation strategy aimed at increasing green spaces and trees cover in the city centre, in order to tackle flood risk and reduce the urban heat island effect (City of London Corporation 2010).

UPA and UPF have been often considered separately, especially in urban contexts. However, the deliberate combination of crops and trees (i.e. agroforestry) can result in more sustainable and resilient systems offering a wide range of ecosystem services, both in the global North and South (Nair 2007). Throughout history, there are numerous examples of diachronic and synchronic *agroforestry* and *agrosilvopastoral* systems, long before these terms were coined and the modern sense of the practices codified.

The aim of this chapter is to outline the benefits deriving from the implementation of urban and peri-urban agroforestry (UPAF) systems, highlighting how the related practices can support the improvement of urban sustainability and resilience, particularly in terms of enhancement of urban ecosystem services provision and urban communities' livelihood.

2 Multifunctional Urban and Peri-urban Agroforestry Systems for Sustainable Land Uses

Agroforestry is a dynamic and ecologically based land-use system, characterized by the integration between woody perennials (trees, shrubs, palms, bamboos, etc.) and crops and/or livestock on the same land management unit. The presence and/or use of woody species and crops/livestock can be simultaneous (synchronic agroforestry systems) or can be organized on a pluriannual basis (diachronic agroforestry systems). Proper management of these systems can optimize the biological, physical and ecological interaction of the different components, while achieving environmental, social and economic advantages for land users at all scales (Lundgren and Raintree 1982; Leakey 1996; Lassoie et al. 2009). Agroforestry is not an innovative practice or technology. Before being replaced by simplified and monoculture production systems, it was practiced for centuries, both in tropical and temperate regions, predominantly in rural areas and less frequently in urban contexts. In this regard, the key question is how did cities interact with these systems and what was their role if any in developing or introducing agroforestry systems in urban and peri-urban landscapes?

Trees have probably been a part of cities since their first development (Miller 2004). Since agriculture led to the first permanent settlements, it stands to reason that wild or domesticated plants were part of the community, including trees cultivated for food as well as for energy, medicines and other non-wood forest/tree products.

Food, wood and water supply relatively close to urban settlements was vital in ancient cities due to transport, safety and strategic reasons. Even if transportation networks developed quite early in human history, the opportunity of having at least a small amount of basic resources close or within the core city area has been decisive in the success or failure of urban experiences at least as much as the morphology and salubrity of sites and the presence water ways and harbour facilities for faster transportation. We should thus assume that the decision itself of placing permanent settlements in a particular location was often linked to the presence of tree species suitable for multiple uses and easily combined in multiple land uses. As example, the use of acorn meals is well rooted in native Americans' diet (Merriam 1918), and the presence of oaks was a crucial aspect in deciding the wintering sites for native Americans (McCarthy 1993).

The early Egyptians described trees being transplanted with balls of soil over 4000 years ago (Chadwick 1971) in the context of cities. Trees were valued for shade and aesthetics and were included in gardens around temples and palaces. It is likely that most trees were selected for their utilitarian value (fruit) as well as their beauty. The Hanging Gardens of Babylon are described in a number of ancient texts, and it is very likely that the structure of the gardens included several agroforestry systems (Miller 2004).

In the cities of ancient Greece, the lack of space and the geographical fragmentation of city-states (*Polis*) influenced the organization of peri-urban and urban landscapes in order to provide multiple resources where trees were associated to agricultural crops. Odysseus says, "Old man, you lack no skill at tending gardens. Everything is well-kept, and there is not a single plant, fig, vine, olive, pear, or garden that lacks your careful attention" (Odyssey 24.244–247. Translation by McCorie).

Dikaiopolis, the central character of Aristophanes' Akharnians, is an Attic farmer who has been forced to settle in the city during the Peloponnesian War

(431–404 BC). During his prologue, Dikaiopolis explains how jarring it is for him to have to pay for everyday commodities. "I miss my home town", he says, "where I never had to buy charcoal, vinegar, or oil. The word 'buy' was not known there, but instead I produced everything myself". Because they grew many different crops on their land, subsistence farmers like Dikaiopolis had little need for the market except during food shortages (MacDowell 1983).

Roman cities developed a wide typology of city gardens. Agroforestry systems were developed in urban and peri-urban areas. The gardens of ancient Pompeii are a tangible example of the organization of green spaces in a city, albeit provincial, 2000 years ago. Ancient Pompeii was not just made of roads and buildings: there were public and private green spaces, and every home, rich or modest, had its garden. Especially the suburban districts around the Amphitheatre, that experienced the inevitable transformations related to urban expansion, hosted a myriad of green areas with different uses: this meant that orchards and gardens for the production of fresh produce were concentrated in a relatively limited space. The archeobotanical remains of *Vitis* associated to tree species suggest the cultivation of vine trained upon elms, field maples and hornbeams in order to maximize the use of space for multiple resources production. Similarly, *Juglans* and *Castanea* archeobotanical remains in the neighbourhood of Neapolis associated to pollens of edible vegetable species suggest the presence of multipurpose agroforestry systems serving the city.

The walled medieval cities in Europe were surprising laboratories of agroforestry practices in urban areas. Despite the ever-told story of city gardens belonging to the nobles or rich families and generally cultivated for fruit, leisure and beauty, most of the cities experienced long periods of food and energy shortage because of the unsafety of the surrounding territories. Urban communities needed to find alternative solutions in term of producing food, energy and medicines within the city walls or in the immediate neighbourhoods of the city. As is still the case today, in the European medieval city, the garden was where the most fragile trees, the ones that require the most care were planted and it is there that new varieties are tested, acclimated and developed. The city garden could well have played a considerable role in the domestication of fruit trees. In parallel, the need of combining wood and food production required the development of structured practices of tree pollarding, topping and shredding combined with small horticultural or agricultural crops inside the city walls. Such practices were later exported to rural contexts maintaining a traditional way of managing both rural and urban trees.

The civilizations of Maya, Inca and Aztecs built large cities with monumental architecture, and they supported their cities with agriculture and agroforestry systems. Drawings and descriptions of pre-Columbian America suggest many native American tribes developed extensive agricultural communities, which included extensive gardens with planted trees (Box 28.1).

The recent renewed scientific interest in agroforestry is due to its potential contribution to sustainable development, thanks to its capacity of remaining productive and supporting a wide range of ecosystem services at the same time, as argued by Mbow et al. (2014), that have recognized the importance of implementing urban and peri-urban agroforestry practices as effective contribution towards the achieve-

Box 28.1 The Case of a Mayan City: Tikal (Lentz et al. 2014)
Tikal has long been viewed as one of the leading polities of the ancient Maya realm. But how was the city was able to maintain its substantial population in the midst of a tropical forest environment up to the mid-9th century A.D. when Tikal was abandoned? The Late Classic Maya at Tikal practiced intensive forms of agriculture coupled with carefully controlled agroforestry and a complex system of water retention and redistribution. Because forests supplied essential resources, such as fuel, construction material, habitat for game, wild plant foods and a pharmacopoeia from medicinal species, agroforestry played a crucial role in the ancient Maya economy. By far, the heaviest demand on the forest was firewood needed for cooking and firing of ceramics. The production of lime (calcium oxide), an essential component of plaster, also required considerable fuel input. Wood required for construction and handicrafts also created an essential but less voluminous demand. The estimated wood quantities required annually for the maintenance of population at Tikal for fuel and construction was 42 million kg·year^{-1}, approximately equal to the amount of wood available on a sustainable basis (39 million kg·year^{-1}) from the Tikal upland and bajo forests. The Maya compensated for any shortages in forest productivity through the importation of pine wood and intensive techniques applied to a fixed plot agroforestry system that contributed up to 10% of the wood supply.

ment of a relevant part of Sustainable Development Goals (SDGs), particularly to the Goal 11: *Making cities and communities more sustainable, resilient, and healthy*.

Furthermore, urban agroforestry implementation is in line with the priorities included in the New Urban Agenda recently adopted in Quito, Ecuador, particularly those referring to the necessity of enhancing food security and nutrition for all, and improving environmental sustainability by promoting sustainable use of land and resources in urban areas.

In particular, the integration of agroforestry systems in urban contexts can consist in a variety of types such as riparian and forest buffers, greenways, windbreaks, urban gardens, roof gardens, homegardens and food forests (Mann 2014). These types, if properly planned and managed, can emphasize the multifunctionality of agroforestry systems, increasing their potential to play a relevant role in improving the sustainability and resilience of urban and peri-urban areas, by providing a variety of ecosystem services related to the enhancement of food and nutrition security and livelihood, by improving soil fertility and biodiversity, by regulating air and water quality as well as by supporting mitigation and adaptation to climate change effects.

Ecosystem services provided by UPAF can be categorized in four main types, as described by the Ecosystem Services Framework (MEA 2005; TEEB 2010):

1. Provisioning services are described as the products obtained from ecosystems. They can include food, freshwater, raw materials and medicinal resources.

2. Cultural services are the immaterial benefits that people obtain from ecosystems such as recreation and mental and physical health, tourism, aesthetic values, spiritual enrichment and sense of place.
3. Regulating services act as regulators. These can provide benefits in terms of local climate and air regulation, carbon sequestration and storage, moderation of natural hazards, waste-water management, soil erosion prevention and pollination or biological control.
4. Supporting services are crucial to provide habitat for migratory species and to maintain the genetic diversity between species populations.

Below, a series of case studies illustrates the way in which the implementation of different types of UPAF practices can provide relevant ecosystem services to urban society and improve the sustainability and resilience of cities and towns.

2.1 Provisioning Services

In the case of provisioning services, urban and peri-urban agroforestry systems, even at plot scale, can play a significant role in supporting urban food and nutrition security, providing the conditions for growing fresh and affordable food for city dwellers (i.e. vegetables, fruits, mushrooms, berries, aromatic spices) and fodder for animal husbandry (i.e. leaves, seeds, sprouts), as well as in enhancing livelihood security from sale of items produced by urban farmers (i.e. food, fodder, timber, plants oil, medicinal plants), especially in low-income countries (Salbitano et al. 2015).

Agroforestry systems in urban areas can also significantly contribute to the sustainable management of water. In fact, trees and vegetation cover, by helping to capture, filter and store water resources, plays a vital role both in supplying high-quality water and in regulating its availability for urban dwellers (FAO 2016).

In addition, agroforestry practices can be an important source of raw materials for construction, especially in regions where there is limited timber available and of energy, providing the wood fuel on which 38% of world's population still relies for cooking and heating, especially in developing Asia and sub-Saharan Africa, as estimated by the International Energy Agency (2015).

2.1.1 Tropical Homegardens and Food Security

Tropical homegardens[3] (Fig. 28.2) are recognized as ecologically and socially sustainable agroforestry systems. This is due to their ecological characteristics – such as efficient nutrient cycling, high levels of biodiversity and limited exogenous inputs

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[3] Kumar and Nair (2004) define tropical homegarden as: "*intimate, multistory combinations of various trees and crops, sometimes in association with domestic animals, around the homestead*".

Fig. 28.2 Tropical homegarden in the Philippines (Source: Thomas Galvez 2016) https://www.flickr.com/photos/69031678@N00/27775415291

required, as well as soil protection and enrichment (Torquebiau 1992; Jose and Shanmugaratnam 1993; Gliessman 1998; Méndez et al. 2001) – and their capacity of providing a variety of socio-economic benefits to the local population, contributing to food and nutrition security, energy needs and livelihood enhancement (Lok 1998; Kumar and Nair 2004; Peyre et al. 2006).

Homegardens in tropical regions represent a well-established land-use system, even though in recent times they are increasingly threatened by growing urbanization, "*agrodeforestation*", (Thaman 1992) and increasing dependence on imported food and fuels (Thaman 1988). However, tropical homegardens still play a key role in enhancing food security of urban and peri-urban dwellers (Kumar and Nair 2004). In fact, as argued by Montagnini (2006), these practices can contribute to local food security in several ways, by fostering direct access to quality and healthy food; enhancing family income, thanks to savings on food bills and on generation of additional income from sale of garden production; and providing food products year-round, especially during periods of food scarcity.

For example, in both Pacific and Caribbean islands, homegardening allows to address food and nutrition security through the provision of local and traditional fruits (mango, avocado, oranges, lemon, papaya, etc.), vegetables (tomatoes, eggplant, bean, etc.) and also some herbs (oregano, coriander, rosemary basil and mint)

(USDA 2015). One of the most widely cited examples is Havana, Cuba, where, as reported by Altieri et al. (1999), in 1996, homegardens provided a significant amount of fresh food to urban population, including 8500 tons of agricultural produce, 7.5 million eggs and 3650 tons of meat.

In addition, multistorey homegardens can provide medicinal plants to the families and communities that maintain them, both for subsistence and marketing purposes. These homegardens are characterized by different layers of plants of medicinal value, including a ground layer (0–1 m), generally constituted by herbs, vines or climbers in combination with vegetables and spices, and a second (1–3 m) and upper layers (>10 m) made up by shrubs and trees (Wezel and Bender 2003; Rao and Rao 2006). The relevance of traditional herbal medicines is witnessed by their widespread use in developing countries, especially in Africa where up to 80% of population is still dependent on them (WHO 2002). Furthermore, if not directly consumed, medicinal resources can be sold for generating additional income. The sale of medicines of natural origin has an estimated global market of US$57 billion per year (Kaimowit 2005).

2.2 Peri-urban Agroforestry and Livelihood Enhancement in Nigeria

Several authors (Drescher et al. 2006; Yamada and Osaqui 2006; Kumar and Nair 2004) have observed how marketing-oriented homegardening as an opportunity to generate additional cash income is increasingly widespread, particularly in the Global South.

A study by Odurukwe (2004) has demonstrated the relevant role of agroforestry practices in peri-urban cities of Abia State, Nigeria, namely, Uzuakoli, Obehie and Isuikwuato. In these cities, one of the main purposes for practicing multistorey homegardening is the chance for inhabitants to improve their livelihoods through income generation. The interviews, involving 180 randomly selected households, highlighted the great contribution of agroforestry in enhancing households' livelihood through the sale of homegardening products, with 75% of the interviewed reporting to have increased their income from selling goods such as fruits, food crops, vegetables, leaves, seeds, bark, fuelwood, etc. In this context, 17% of respondents reported to an additional annual income of between USD 180 and 270, 52% declared an average amount of between USD 90 and 180, and only 31% of households earn around USD 90. However, despite the great potential of peri-urban agroforestry for generating additional cash income, in Abia State, this land use is limited by the lack of sound planning, management and monitoring, in order to avoid conflicts with other land uses and problems related with land ownership.

2.3 Cultural Services

In addition to the production of material goods (food, fibre and other non-wood forest products), UPAF can also provide a variety of immaterial services. As argued by Barthel et al. (2010, 2013), agroforestry practices in urban areas can help communities maintain "socio-ecological memory" described as "*the combined means by which knowledge, experience and practice of ecosystem management are captured, stored, revived, and transmitted through time*"; this brings an important educational value to urban dwellers, raising awareness of the importance of links between urban ecosystem services and human well-being (Camps-Calvet et al. 2016), helping to overcome the so-called "extinction-of-experience" (Pyle 1978) or "global generational amnesia" (Miller 2005) and connecting older and younger generations.

Moreover, urban agroforestry practices are also recognized as important source of psychological, health and social benefits for urban dwellers and city users, contributing to stress reduction (Ulrich 1981), providing a sense of peacefulness, beauty and freedom (Kaplan 1983) and also fostering social interaction and integration among residents (Coley et al. 1997). Finally, in terms of aesthetic, historical and recreational values, agroforestry systems can provide a more pleasant and liveable urban landscape by offering different colours, shapes and textures that vary according to season and weather conditions (Miller 1997), as well as increase city's attractiveness as a tourist destination (Chiesura 2004).

2.4 Beacon Food Forest

For the past two decades, the Seattle Department of Neighborhoods has provided funding for green infrastructure programs, focusing particularly on the provision of environmental services and food production, through the implementation of street tree planting and other greening projects around the city. More recently, the Department shifted its vision in order to incorporate urban forests into the city as a whole (McLain et al. 2012). The development of the Beacon Food Forest (Fig. 28.3), a community-driven food forest, started in 2009 combining aspects of native habitat rehabilitation and edible forest gardening. The forest was to cover a 7-acre public land in the Beacon Hill neighbourhood, an area characterized by high levels of cultural diversity.

Initially designed by four students as final project for a permaculture design course, the food forest concept was later presented both to the community and to Seattle City agencies and become part of the Seattle Department of Neighborhoods P-Patch Community Garden Program, benefitting from expert support and public funds for the community design process and the subsequent implementation (Seattle Department of Neighborhoods 2016). Thanks to the community involvement and the local authorities' support, phase one of the project started in 2012 and was con-

Fig. 28.3 The beacon food forest (Source: Flickr/Wright J 2013) https://www.flickr.com/photos/eakspeasy/9180679958/in/photolist-eZ57tK-dgp3SZ-dgp3Wk-eN4F8e-eZgsbf-dgp3wZ-dgp2YF-eZgma1-eZ549g-eZgr4G-eZ4WSp-eZgoiu-dgp3Nx-dgp58N-dgp2b8-eZguBy-eZgsyw-eN4F1Z-eZgu7f-eZgnvW-eZ54F4-eZ51cc-eZgtNy-eZ4YUe-eZ4WqP-eN4BMc-eNg6k5-eh

cluded in 2014, initially covering an area of 0.8 ha that was made available by the landowner, Seattle Public Utilities, with the possibility of expanding the project in the future according to the interest and support of the community.

The Beacon Food Forest aims to foster community and social justice building through an integrated agroforestry woodland food system including several layers with fruit and nut trees (providing sustenance and shade), forming the upper level, and berry shrubs, perennials and annuals (for free gleaning and picking), forming the ground layer. In addition, the project includes a community garden to allow families to grow their own food, a gathering plaza used for celebration and educational activities and kids' area for education and play (Beacon Food Forest 2016).

Indeed, besides the improvement of local food security and ecosystem, Beacon Food Forest's main goal is to provide work and educational opportunities for students and disadvantaged groups, while at the same time strengthening community connections, raising environmental awareness and improving knowledge on food forest principles and permaculture practices.

2.5 Regulating Services

By playing a relevant role as a regulator of ecosystem processes, UPAF contributes to the environmental sustainability and resilience of cities. By providing shade and increasing evapotranspiration, properly planned and placed agroforestry systems can significantly mitigate the urban heat island effect and reduce the energy demand of buildings for heating and cooling. Moreover, agroforestry is increasingly recognized as climate-smart practice (FAO 2013) for its capacity of regulating local climate by above and below ground carbon sequestration and storage, although its carbon capture and sequestration potential are influenced by several variables such as species composition, age structure, climate context and management system (Jose 2009).

Water cycle optimization and storm water runoff regulation are also important services provided by the integration of trees and crops in urban areas. Furthermore, by intercepting rainfall, tree and vegetation cover helps in mitigating soil loss and soil erosion. Acting as filters, urban agroforestry patches help remove pollutants from the atmosphere improving air quality through the absorption of ozone, sulphur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (Nowak 1994; Escobedo et al. 2008).

2.5.1 Multifunctional Agroforestry for Climate Change Adaptation in Bobo-Dioulasso

According to the 2006 census (INSD 2007), Bobo-Dioulasso, with a population of nearly 500,000 inhabitants, a growth rate of 7%, and an extension of 160,000 ha of which approximately 19% is built environment, is the second largest city of Burkina Faso, after its capital, Ouagadougou. The city, as many others in sub-Saharan Africa, is experiencing a rapid population growth associated with the fast transformation of rural to urban land use, resulting in the increase of impervious surfaces and vegetation reduction. These dynamics, coupled with climate change effects, are negatively impacting on rainfall patterns, land surface temperatures – which increased by about 6% in the 1991–2013 period (Di Leo et al. 2016) – as well as on agricultural and livestock productivity.

Bobo-Dioulasso plays a key role in the national economy. It is recognized as the economic capital of the country because of the relevance of its textile industry and agricultural activities and production. In this light, the impacts of climate change, negatively affecting the natural resources that are essential for industrial and agriculture production, could jeopardize not only the local, regional and national development but also the social and political stability of the country (UN-Habitat 2014; Ricci et al. 2015). In order to address the negative impacts of urbanization and climate change, the Bobo-Dioulasso municipality has promoted multifunctional urban and peri-urban agroforestry on urban greenways as a climate change mitigation and adaptation strategy (Fig. 28.4).

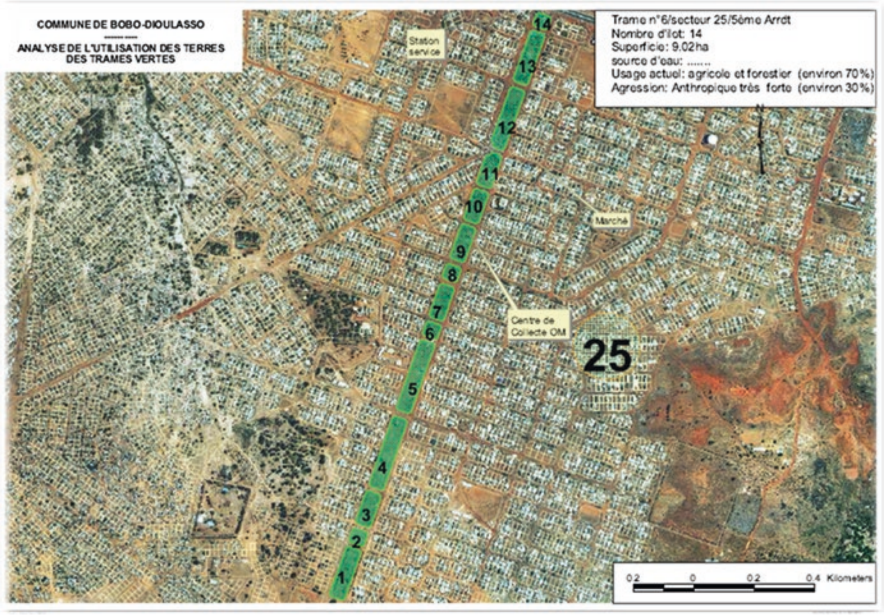

Fig. 28.4 Bobo-Dioulasso greenways strategy (Source: Commune de Bobo Dioulasso 2014)

This strategy is one of the outcomes of the UN-Habitat Cities and Climate Change Initiative (CCCI) in Bobo-Dioulasso. In particular, by carrying out a participative and consultation process aimed at identifying the current and future climate risks for the city and involving a wide range of local stakeholders, the CCCI has defined and adopted a Participatory Climate Risk Management Framework (PCRMF), which was operationalized through the development of the greenways project, supported by UN-Habitat and coordinated by RUAF (Ricci et al. 2015).

Vacant lands within the city were transformed into green corridors through the establishment multifunctional agroforestry systems aimed at mitigating the urban heat island effect and reducing surface runoff, as well as enhancing the resilience of urban dwellers by providing additional food and income sources (Sy et al. 2014). By 2012, eight greenways covering approximately 60 ha were established in the city. These green corridors, connecting the city with its peri-urban forests, provide multifunctional land uses and several functions to urban dwellers, such as forest production, market gardening and provision of recreational and educational spaces (UN-Habitat 2014). They represent a model of sustainable urban development, tackling climate change and enhancing urban ecosystem services in and around the city.

Fig. 28.5 View of city of Vigo (Source: Flickr/Foxspain Fotografia 2008) https://www.flickr.com/photos/foxspain/3216229210/in/photolist-5Ud1TL-dJcxX3-8LX4nE-PG2T2-orBkss-7aqBmf-otrgd1-pFHKrw-7aqBmm-8d6SjC-8A8ByC-4pYSPb-8xRWmn-pFHLnE-ppeYE5-otrfqQ-5V7Tje-dzTfrH-oc9p9N-7Ji9uM-7Jn2U3-7wCaoB-orBgN3-o6ZBK-otre5o-otr9G5-27w9Sk-ocaFh

2.6 Supporting Services

Urban and peri-urban agroforestry plays an important role in providing habitat for migratory species and species that can tolerate a certain level of disturbance. It can help reduce the conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems. By creating corridors between habitat remnants, it can support the conservation of area-sensitive plant and animal species, and finally it can help conserve biological diversity by preventing the degradation and loss of surrounding habitats (Jose 2009).

2.6.1 City Region of Vigo: Multifunctional Management of Common Lands

In the city region of Vigo, Galicia, Spain, a major portion of the metropolitan area consists of green infrastructure components (Fig. 28.5), including public parks, private land lots and privately owned but commonly managed areas, the so-called *Commons*. In the case of Vigo, according to traditional land use, the *Commons* are located in mountain area, called *Monte*, and characterized by the presence of forests, scrubs and bushes. In the city region of Vigo, there are approximately 100 Commons managing 32% of the total metropolitan area.

The *Commons* way of managing land, which was oriented to a multifunctional approach to agriculture, agroforestry, silviculture and animal husbandry, was dramatically changed during Franco's dictatorship (1939–1975) to initiate afforestation campaigns by using mainly *Eucalyptus*. In the last two decades, some *Commons* in the city region are recovering their multifunctional use, as well as the diversity and variety of landscape mosaic. The *Commons* of Vinicios (10 min to the centre of Vigo) implemented several projects for biodiversity and active landscape conservation, forest food production and cultural and social issues. Re-establishing former agroforestry systems, either formal or informal, constitutes one of the key steps in restoring the multifunctional structure of the landscape, including the potential of peri-urban agroforestry to provide supporting ecosystem services (Garcia et al. 2015).

3 Key Challenges

As many other land uses, urban agroforestry faces a number of challenges for implementation that are very similar to those encountered by urban agriculture and urban forestry. In particular, when considering the establishment or the conservation of agroforestry systems in urban settings, it is important to be aware of the following issues:

Land Tenure A well-defined land tenure framework is essential for enhancing the potential of UPAF in any given location. Indeed, people are usually unwilling to plant trees on land for which they do not have guaranteed long-term access, either as owners or leaseholders. Land-use conflicts are often more severe due the pressure of urban growth, so it is essential to establish clear rights on the land and robust platforms for conflict management.

Urban Planning Urbanization has caused major changes in land use and landscapes in and around cities. Comprehensive urban plans should support UPAF and provide frameworks for implementing land-use regulations in an effective and transparent manner. They should also ensure that planning of green spaces, including areas that are designated for urban agroforestry, receives equal attention in the urban planning process as the elements of the built environment are viewed as key elements of the urban fabric, providing the city with the ecosystem services listed above.

Technical Knowledge Agroforestry systems are more knowledge intensive than ordinary agriculture systems in view of their relatively higher complexity. The information available to agroforestry practitioners in urban areas could be increased through extension services and field schools, which could be provided by local organizations (such as farmer associations), and through the provision of e-learning, toolkits, plot demonstrations and farmer–farmer exchanges.

Governance The governance of green infrastructures requires that planning departments have the necessary technical skills and knowledge to include urban agroforestry in the overall planning process. It is also essential that the community has the capacity to act on the opportunities provided by the governance process. This may be the case in only some groups or for certain individuals. In any case, innovative urban agroforestry governance requires education and capacity building. Depending on the local conditions, governance can follow different models ranging from full self-governance of land users to a more comprehensive governmental regulatory framework.

These of course are only some of the challenges that will be faced in establishing urban agroforestry systems. Other possible issues to be addressed include lack of intersectoral coordination, access to markets, food safety as well as access to credit.

4 Conclusions/Way Forward

From the experiences described above, it is quite apparent that UPAF is a widespread practice in both low-income countries and as well as in the so-called developed world. UPAF, like urban agriculture and urban forestry, promotes inclusiveness in terms of involving experts, policy makers and communities, and it is crucial to ensure that any initiative is fully integrated with other comprehensive approaches to natural resources management and land use within the city boundaries, at the urban fringe and at the urban–rural interface. These include urban greening, green infrastructure planning, nature conservation, forestry and agriculture. All these elements can contribute to improve urban living conditions and livelihoods and can help cities "farm for the future". Land should not be seen as a space for conflict between urban forestry, urban agriculture, urban agroforestry and urban recreation but should rather be the space to create integrated opportunities for maximizing benefits to urban dwellers.

More effort is needed in identifying the most suitable combination of productive, environmental and socio-economic functions and in designing the most effective mosaic of "green" land uses suited to the different conditions of individual cities.

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Chapter 29
Mitigation and Adaptation Strategies to Climate Change Through Agroforestry Practices in the Tropics

S. L. Swamy and V. P. Tewari

Abstract The rapidly increasing concentrations of greenhouse gases (GHGs) in the atmosphere are mainly responsible for global warming and consequences of climate change. Agriculture is the mainstay of livelihood and food security to millions of people living in tropical countries; climate change is posing a serious threat on food production, nutritional security, and livelihoods of poor farming communities of developing countries. This has prompted a renewed interest in mitigation and adaptation strategies to minimize negative impacts of climate change on agroecosystems through introducing promising tree-based alternate land-use systems. Agroforestry systems (AFS) indeed offer viable opportunity to mitigating the atmospheric accumulation of CO_2 and other greenhouse gases and potential for transforming into resilient farming systems and help the farmers in adapting to climate change in tropics. The potential of AFS to accumulate carbon (C) was estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1}. Agroforestry practices also offer climate change adaptation by means of buffering agricultural crops against water deficiencies through ameliorating microclimate, maintaining long-term soil health, and minimizing the incidence of insect and pests under climate change scenarios. The degree of mitigation and adaptation varies according to the structural and functional complexities of systems. In addition, agroforestry systems will provide many tangible benefits to farming communities in the form of food, fuel wood, fodder, timber, medicine, fiber, etc. and be able to address the diverse issues of livelihoods, unemployment, and poverty. Agroforestry systems in developing countries shall ensure the farmers in gaining additional economic benefits of C sequestration by C trading with developed countries under CDM projects. It will help the farmers to improve their farm economy besides securing environmental benefits to global communities. The chapter discusses the potential role of agroforestry systems for mitigation and adaptation to climate change and buffering climate extremities in diverse socioeconomic and environmental setups in tropics.

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1 Introduction

One of the major issues of global concern today is increasing levels of greenhouse gases (GHGs) and their consequences on climate change. Anthropogenic activities, viz., inappropriate land-use practices, excessive fossil fuel combustion, and rapid industrial expansion, are mainly responsible for accumulation of greenhouse gases into the atmosphere causing global warming (Albrecht and Kandji 2003). The major greenhouse gases accountable for this phenomenon are carbon dioxide, methane, NOx, and chlorofluorocarbons. CO_2 is the most culprit gas, which alone majorly contributes to global warming. The emissions of CO_2 increased dramatically from 280 ppm in preindustrial era to 399 ppm in 2015 and are predicted to be almost double to preindustrial level by 2050 (IPCC 2014). The concentrations of methane and NO_X were also significantly enhanced up to the tune of 1890 ppb and 326 ppb (IPCC 2014). Due to increase in levels of greenhouse gases, the earth's temperature is already increased by 1–1.5 °C in the last 100 years and further predicted to rise by 2.5–3.0 °C by 2050, if the same rates of emissions are continued (IPCC 2014). The extreme weather events are occurring due to abrupt change in intensity and patterns of rainfall and temperature, which is attributed to rapid climate change. There are overwhelming evidences of negative impacts of climate variability on structure and functioning of many terrestrial ecosystems (Verchot et al. 2007; Nath and Behra 2011; Sheshta et al. 2014; Jat et al. 2016). Agriculture, a human developed enterprise, is highly dependent on specific climate conditions. Climate change is likely to influence crop and livestock production, hydrological balances, input supplies, and other components of agriculture system. The magnitude of impact varies across the agroecological regions of the world.

2 Impact of Climate Change on Agriculture

Agriculture is the mainstay of livelihood and food security to millions of people living in tropical countries (Adams et al. 1998; Nath and Behra 2011). Agriculture sector is extremely climate sensitive and explicitly vulnerable to climate change. The climatic variations causing frequent floods, droughts, windstorms, and outbreaks of pests and diseases increase the incidences of crop failures in many regions. The economic, social, and nutritional securities are emerging as serious challenges to humankind. More than 800 million people in the world are chronically malnourished, and 1100 million live in absolute poverty (Verchot et al. 2007). The population of developing countries, particularly in South Asia and sub-Saharan Africa, continue to grow at high rates, while the food production is gradually declining. The food production needs to be doubled within the next 20–30 years (Verchot et al. 2007). The shortfall in cereal production in the developing world is expected to widen the gap between demand and supply. The lack of new varieties and increased fertilizer use to further increase yields degrade the ecosystem and will undermine future efforts to boost agricultural productivity. Several studies have shown decrease in the growing season as temperature increases and depleted the yields of crops (Lal 2008). Higher temperatures increase evapotranspiration and decrease winter precipitation which may bring about more droughts. Changes in precipitation patterns and amount and changes in temperature will affect crop growth through changes in soil water content, runoff and erosion, workability, nutrient cycles, salinization, biodiversity, and soil organic matter (Rao et al. 2007; Jose 2009; Sushant 2013; Mbow et al. 2014). The cyclonic storms, storm surge, and coastal inundation also lead to catastrophe. High temperature leads to increase in respiration rates, short periods of seed formation, and consequently lower biomass production. Such reductions were only partially offset by a positive response to increased CO_2 concentrations as CO_2 fertilization effect. Increase in precipitation shall benefit arid and semiarid regions by increasing soil moisture, while aggravating the problem in regions with excess water. There are other stressors also which antagonistically influence along with climate change process (Luedeling et al. 2014).

Climate change coupled with unsustainable agricultural practices like excessive use of fertilizers, pesticides, and herbicides to enhance food production has further aggravated the environmental problems. Productive agricultural systems are gradually turning into unproductive systems affecting the livelihood and economy of small and marginal farmers. Some effective measures are initiated by communities but are not enough as the primary drivers of climate change are not going to halt. Therefore, the emphasis is given on mitigation and adaptation of agricultural systems to reduce the vulnerability and risks associated with climate change (Nair et al. 2009; Nath and Behera 2011). Climate change has emerged as a global issue where efforts for mitigation and adaptation to changing conditions have been strongly recommended by the Intergovernmental Panel on Climate Change (IPCC 2014). Mitigation refers to lessening of the impact of climate change which can be achieved either by reducing the source of emissions of greenhouse gases at source level or by capturing them from the atmosphere and locking them in the diverse ecosystems and expanding the sinks. In recent years, the mitigation measures in the agriculture and forestry sectors together simulated a lot of interest as a potential source for additional income and also as a means of adaptation strategy to climate change. Within the United Nations Framework Convention on Climate Change (UNFCCC) negotiation process, the development of mitigation and adaptation activities attracted new dimensions for negotiating the problems (IPCC 2014). The potential synergies between adaptation and mitigation measures need to be carefully exploited in addressing the current situation.

The understanding of the link between adaptation and mitigation measures is quite useful for planners and policy makers. There is a growing interest in developing resilient agricultural systems to withstand against climate change. Increasing system resilience is directly related to increasing the adaptive capacity of farmers, which is intricately linked to social and economic status. Sustainable agricultural development is essential not only to ensure the food supply but also alleviate poverty through economic growth by creating additional employment opportunities in nonagricultural rural sectors (Antle et al. 2007). It is possible that climate change may force the pace of rural-urban migration (urbanization) over the next few decades. Innovative technologies and policies are required to strengthen the capacity of communities to cope effectively with both climatic variability and changes. Agricultural lands are believed to be a major potential sink and could absorb large quantities of C if trees are reintroduced to these systems and judiciously managed together with crops and/or animals (Nair and Nair 2014). Thus, the importance of agroforestry as a land-use management is receiving wider recognition not only in terms of agricultural sustainability but also in issues related to climate change (Pandey 2002). Agroforestry systems could potentially sequester significant amount of C per year. Agroforestry, a tree-based agriculture land-use system, is recognized as cost-effective and beneficial technologies proved as viable intervention. It not only offers opportunity for mitigation and adaptation to climate change but also secures a large number of tangible benefits, viz., food, fuel wood, fodder, fiber, timber, medicine, etc., and intangible services like biodiversity conservation, slope stability, runoff control, soil and water conservation, etc. (Jose 2009; Nair et al. 2009; Mbow et al. 2014).

3 Climate Change Mitigation Through Agroforestry Practices

Agroforestry is an age-old practice which integrates trees, shrubs, and animals with annual crop production to ensure steady supply of food and/or income throughout the year; arrest degradation and maintain soil fertility; diversify income sources; enhance the efficient use of soil nutrients, water, and radiation; and provide regular employment (Rao et al. 2007). Agroforestry can both sequester carbon and produce a range of economic, environmental, and socioeconomic benefits (Jose 2009). The perennial trees/shrubs are capable of absorbing large amounts of atmospheric CO_2 through photosynthesis and store C in long-lived and short-lived biomass components in addition to enriching the soil productivity. For example, trees in agroforestry farms improve soil fertility through maintenance of soil organic matter and physical properties, increased N, extraction of nutrients from deep soil horizons, and promotion of more closed nutrient cycling (Montagnini and Nair 2004). Combined yields of tree, crop, and livestock products from well-planned and well-managed agroforestry systems tend to be higher than those from sole systems due to increased and efficient use of scarce resources. Agroforestry systems therefore can enhance resilience by diversifying the production base and ensure the risks involved in mono-cropping due to climate change. Promising agroforestry systems capable of ameliorating microclimate, arresting soil degradation and restoring soil fertility, and diversifying income-generating opportunities were evolved in tropics in the last few decades (Table 29.1).

Table 29.1 Some prominent agroforestry systems and practices in tropics

Agroforestry system	Practices	Combination	Components
Agri-silvicultural system	Shifting cultivation/ improved fallow	Trees grown in noncrop period	Fast-growing trees, agricultural crop
	Taungya	Intercropping in initial stages of establishment of trees	Plantation of tree species and agricultural crops
	Hedgerow intercropping	Perennial trees such as woody hedges and crops in alleys	Woody trees with coppicing ability and crops
	Tree gardens	Multiple species, dense mixed	Fruit trees shade tolerant
	Multipurpose trees on farm lands	Trees scattered on field/ boundaries	Multipurpose trees and crops
	Plantation crops	Shade trees with plantation crops	Coffee, coconut, fruit trees, and shade-loving crops
	Shelterbelts, wind breaks, live fences	Trees/shrubs in single or multi-rows	Multipurpose trees on boundaries plus crops
	Homegardens	Multi-strata systems around homes	Multipurpose fruit, timber trees with crops
	Farm woodlots	Firewood and MPTs	Trees and crops in separate settings
Agri-silvipasture system	Homegardens with animals	Multi-strata system around home with fodder trees	Coppicing fodder trees, fruit trees, plantation crops, and crops
	Multipurpose woody hedgerows	Multipurpose trees such as woody hedges with crops	Leaves forage for animal rearing with crops
	Aqua-forestry	Trees on the bunds of ponds	Multipurpose trees forage
Silvopastural system	Trees on rangelands	Scattered fodder trees in combination with grasses and legumes	Scattered trees on rangelands, grasses, and legumes
	Protein/fodder banks	Fodder trees in association with forage crops	Fast-growing leguminous trees fodder crop
	Plantation crops with pasture	Plantation crops along with grasses	Plantation crops like rubber, coconut, coffee, cashewnut etc. with forage grasses
	Riparian buffers	Combination with trees and natural grasses along the stream banks	Multipurpose trees in association with natural grasses and legumes

Source: Rao et al. (2007)

The tropical agroforestry systems are distinguished by their distinctive spatial and temporal dimensions and structural and functional complexities. Agrisilviculture system integrates annual food crops along with trees simultaneously or sequentially and mainly includes improved fallows, taungyas, alley cropping, plantation crops, shelterbelts, woodlots, homegardens, etc. practiced in various ecological and socioeconomic situations (Rao et al. 2007). The systems are designed for simultaneous production of food along with wood products, etc. On the other hand, agri-silvopasture is a more complex system aimed at concurrent production of food, fodder, wood, and animal, which includes homegardens with animal, multipurpose woody hedge rows, aqua forestry, etc. (Nair et al. 2010). Silvopasture system incorporates fodder trees, grasses, and legumes for the concurrent production of timber and forage for animal rearing. It includes rangelands with scattered trees, protein/fodder banks, riparian buffers, etc. All these systems by and large provide multiple benefits to the societies and secure local as well as global interests.

4 Carbon Sequestration in Plants Under Agroforestry

Although most of the agroforestry systems are potential sinks, however some practices like shifting cultivation, pasture maintenance by burning, manuring, nitrogen fixation, N fertilization, frequent disturbances in soil, and animal production can act as source of GHGs. Carbon sequestration involves the net removal of CO_2 from the atmosphere and storage in long-lived pools of C. Such pools include the aboveground plant biomass; belowground biomass such as roots, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments; and the durable products derived from biomass (Soto-Pinto et al. 2010). The significance of agroforestry with regard to C sequestration and other CO_2 mitigating effects is now widely recognized. According to an estimate, 630×10^6 ha are suitable for agroforestry in the world and have strong potential to sequester C across the world (Nair et al. 2009; Jose 2009). A major portion of this area lies in tropics and currently under some or other agroforestry practices, which could be further efficiently utilized for C sequestration by intensifying management practices. The C sequestration potentials of tropical agroforestry systems are highly variable (Albrecht and Kandji 2003). C storage in agri-silvicultural systems in humid tropics is relatively higher compared to silvipasture systems and range lands (Kaur et al. 2002). According to a study, shifting from traditional fallow to traditional maize caused a total living biomass carbon loss of 94%, and shifting from traditional fallow to improved fallow, taungya, or coffee prototypes maintains carbon in living biomass (average 50 Mg C ha^{-1}) (Soto-Pinto et al. 2010; Nair and Nair 2014), whereas changing from pasture toward silvopastoral systems increased carbon in living biomass by 20 times. Similarly, the multi-strata complex systems in homegardens have an advantage of higher number of components and could sequester more C as compared to less complex agri-silvicultural system (Nair et al. 2010). The agroforestry systems have more C than simple row crops and fallow

Table 29.2 C storage potential in agroforestry systems

Continents	Eco-region	System	Mg C ha^{-1}
Africa	Humid tropical high	Agrosilvicultural	29–53
South America	Humid tropical low dry lands	Agrosilvicultural	39–102
			39–195
Southeast Asia	Humid tropical dry low lands	Agrosilvicultural	12–128
			68–81
Australia	Humid tropical low	Silvopastoral	28–51
North America	Humid tropical high	Silvopastoral	133–154
	Humid tropical low dry lands	Silvopastoral	104–198
		Silvopastoral	90–175
Northern Asia	Humid tropical low	Silvopastoral	15–18

Source: Albrecht and Kandji (2003)

lands. The potential of AFS to accumulate carbon (C) is estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1} (Albrecht and Kandji 2003; Soto-Pinto et al. 2010). Agroforestry systems in the arid, semiarid, and degraded sites have a lower CSP than those in fertile humid sites; and the temperate agroforestry systems have relatively lower vegetation CSP than the tropical ones. A comparative account of C sequestration under different agroforestry practices is presented in Table 29.2.

One of the major issues of keeping the soil resource productive and in place could be accomplished by means of maintaining the levels of soil organic carbon. Agroforestry systems help in improving the status of organic C in the soil. Scientifically acceptable evidence to support the positive influence of trees in enhancing soil organic C is overwhelming (Chavan et al. 1995; Swamy and Puri 2005; Swamy and Mishra 2014). It is an established fact that soil factors (type, water content, pH, aeration, microflora, and so on), climatic conditions (temperature, rainfall), and litter fall (quantity) determine the soil resources. In this context, it is envisaged that the increased litter input and addition of root residues under agroforestry practices shall improve C storage in soil. According to a study conducted in humid tropics, agroforestry systems have the potential to sequester more than 70 Mg ha^{-1} in the top 20 cm of the soil (Soto-Pinto et al. 2010). Earlier studies showed that a significant increase in C was observed in the topsoil even after short duration of 5-year plantation. Soil organic C accretions through employing improved fallow were estimated to be between 1.69 and 12.46 Mg ha^{-1} (Soto-Pinto et al. 2010). Many studies indicated that the most marked differences in soil organic C are in the upper soil layer in plantations (Chavan et al. 1995; Fang et al. 2007; Gupta et al. 2009; Chauhan et al. 2012). However, the deeper layer seems to be more stable and responds to long-term sequestration. The higher amount of leaf litter and root residues in surface soil layer could be attributed to higher C pool as opined by many researchers (Swamy and Mishra 2014). The amount of C sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socioeconomic factors. Other factors influencing carbon storage in agroforestry systems include tree species, structure and function of different components, and system management (Nair and Nair 2014).

Although most of agroforestry systems are potential sinks, some practices like shifting cultivation, pasture maintenance by burning, manuring, nitrogen fixation, N fertilization, frequent disturbance in soil, and animal production can act as sources of GHGs. Silvopastoral systems, improved fallow, taungya, and coffee systems (especially polyculture-shade coffee and organic coffee) also have the potential to sequester carbon by maintaining polyculture and optimum number of trees (Soto-Pinto et al. 2010). Agroforestry systems could also contribute to carbon sequestration and reduce emissions when burning, and frequent tillage is avoided. A study conducted in Zimbabwe, Africa, showed that in improved fallow-maize rotation system, N_2O emissions were found to be almost ten times to those of continuous unfertilized maize, but these levels were still extremely low when compared to the increase in the amount of carbon stored (Jat et al. 2016). Therefore, there is a need to optimize the tree-crop-animal component combinations and adopt an integrated management to help in minimizing the sources and enhance the sink potential for better adaptation and mitigation of climate change through agroforestry.

5 Adaptation to Climate Change Through Agroforestry Interventions

Adaptation is believed to enhance the resilience of ecosystems against increasing climate variability. It is now increasingly accepted as a viable strategy to reduce the vulnerabilities of climate change. Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic change and their negative impacts (Antle et al. 2007). It mainly includes processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change. Adaptation to climate change has the potential to substantially reduce many of the adverse impacts on agriculture and enhance beneficial impacts though neither without cost nor without leaving residual damage.

Agroforestry practices offer the most viable opportunities to climate change adaptation and promote the maintenance of agricultural production by making resilient agricultural system (Nair and Nair 2014; Swamy and Mishra 2014; Sheshta et al. 2014; Jat et al. 2016). The perennial tree component of agroforestry system efficiently utilizes the scarce resources available in climate change scenarios and minimizes the risks involved in mono-cropping. In low-rainfall years, water availability may further decline, cause frequent droughts, and decrease food production. Agroforestry systems help in buffering agricultural crops against water deficiencies through ameliorating microclimate by influencing radiation flux, air temperature, wind speed, saturation deficit of understorey crops all of which will have a significant impact on modifying the rate and duration of photosynthesis and subsequent plant growth, transpiration, and soil water (Rao et al. 2007; Lin 2007). The shading of trees further reduces heat stress and controls wind storms, thus saving crop failure in extremely hot dry season. Some examples where the beneficial aspects of microclimatic changes are extensively used are shade trees to protect heat-sensitive crops like coffee, cacao, ginger, and cardamom from high temperatures, wind breaks and shelterbelts to slow down wind speed to reduce evaporation and physical damage to crops, mulches to reduce soil temperature, and various crop tree mixes to reduce erosion and maximize resource use efficiency (Lin 2010). However, the magnitude of microclimatic modification depends on spatial and temporal arrangement of trees and architecture and phenology. In the semiarid and arid regions, farmers are exploiting the benefits of agroforestry practices providing buffering effect against climate change (Jose 2009). Mulching practices in hedge row intercropping systems in semiarid regions are proved to be a best practice for conservation of soil moisture, enhancing soil fertility, and minimizing the yield losses. The addition of mulch can lower soil temperatures, reduce evaporation, and improve soil fauna activity and soil structure resulting in better infiltration, reduced runoff, and improved water-use efficiency. On sloping land, the tree rows act as a physical barrier to soil and water movement, resulting in significant reductions in erosion losses.

In another study conducted under coffee-based agroforestry systems, crops grown under heavy shade (60–80%) were kept 2–3 °C cooler during the hottest times of the day than crops under light shading (10–30%) and lost 41% less water through soil evaporation and 32% less water through plant transpiration (Lin 2007). Windbreaks planted in citrus groves have been shown to reduce wind speeds by 80–95%, reducing wind damage up to two times the distance of windbreak height (Rao et al. 2007). Shelterbelts in coastal areas have the potential to reduce the flood damage in extreme weather events during cyclonic storms, control wind and water erosion, and restrict the movement of salt-laden winds. Shelterbelts/windbreaks effectively change microclimates and decouple the climates of sheltered areas from those that are unsheltered. Thus, it is expected shelterbelts would be effective and function under a wide range of climate change conditions.

A crop modeling study in eastern Nebraska found that sheltered maize production continued to perform better than unsheltered crops under a wide range of projected climatic conditions. The scenarios considered included temperature increases up to 5 °C, precipitation levels up to 70–130% of normal, and wind speed changes of plus or minus 30%. A study conducted in poplar-based agri-silviculture showed that there was a decrease in leaf temperature and transpiration rates in soybean and wheat grown under poplar clones (Swamy and Mishra 2014). Climate change processes result in soil degradation in tropics. Higher temperatures and drier conditions lead to lower organic matter accumulation in the soil resulting in poor soil structure, reduction in infiltration of rain water, and increase in runoff and erosion. Agroforestry practices have the potential for restoring soil health by ameliorating the physical, chemical, and biological properties of soil. The continuous enrichment of organic matter and efficient nutrient cycling under agroforestry system help in maintaining long-term soil productivity (Kandji et al. 2006; Nair et al. 2009).

Pests, diseases, and weed incidences may likely to increase in tropical agroecosystems with changing climate (Jat et al. 2016). The huge losses in crop production may be encountered due to increased epidemics in warmer climate. Agroforestry offers a range of tools to reduce the disease losses and achieve sustainable production (Pumarino et al. 2015). Agroforestry systems enhance the diversity and complexity and could minimize the incidence of pests and diseases by slowing the spread of water and aerosol-dispersed pathogens. Trees and shrubs often provide better shelter and mating sites than do short-lived annual plants. Studies indicated that hedges provide very favorable environments for parasitic Hymenoptera and Diptera. The humid conditions in an agroforestry system may be favorable for the development of disease in insect pests (Pumarino et al. 2015). Coupled with the absence of direct sun, the effectiveness of entomopathogenic fungi may be increased by humidity. Enhancing plant biodiversity and mixing tree and herbaceous species in agricultural landscapes can produce positive interactions that can contribute toward controlling pest and disease outbreaks. Studies also demonstrated that introduction of flowering perennials or short-lived plants in an agroforestry system will contribute toward biological control of pests. Monoculture crops are likely to be more prone to attack of pest compared to polycultures (Sieshi et al. 2007).

The degree of structural and functional complexities of agroforestry determines the risks of insect pests. Many epiphytic, endophytic, and microbial associations with perennial trees contribute to natural biocontrol of plant diseases. Besides agroforestry system often creates conducive environment by modification of microclimate to harbor a range of parasite and predator population, which will act as natural enemies in reducing the incidence of infestation of pests and diseases (Jose 2009). Greater colonization and abundance of natural enemies in a mixed culture of plants have been demonstrated in many previous experiments. Polycultures, especially those containing flowering trees and shrubs, can provide more pollen and nectar sources attractive to and sustaining predators than monoculture. Agroforestry also provides shelter and nesting habits for many insectivorous birds and bats. Most of the birds play a useful role in agriculture by decreasing the number of insect and other pests. Insectivorous and carnivorous species are useful to agriculture since they keep a very potent check on populations of insect and rodent pests of crops (Jat et al. 2016). The exudates from tree components like stems, roots, and leaves also repel certain insects from crop lands managed under agroforestry systems. Still a lot of understanding is needed to comprehend the complex interaction in crops grown under different agroforestry practices. In simultaneous agroforestry systems, a number of factors governing tree-crop-environment interactions, such as diversity of plant species, host range of the pests, microclimate, spatial arrangement, and tree management modify pest infestations by affecting populations of both herbivores and natural enemies. Further, trees also influence pest infestations by acting as barriers to movement of insects, masking odours emitted by other components of the system and sheltering herbivores, and natural enemies (Rao et al. 2007; Sieshi et al. 2007). Trees also affect pest infestations by acting as the system and sheltering herbivores and natural enemies (Sileshi et al. 2007).

Climate change also poses a serious threat to agricultural systems by increasing the incidence of invasive weeds. The germination and growth of most weed species are usually stimulated by exposure to light. Thus, some control of weeds may be affected if a closed canopy can be maintained during the fallow period in an alley cropping system (Nair et al. 2009). In agroforestry shading by trees suppresses the weed proliferation and growth. Trees also suppress weed growth through the litter layer which forms from natural leaf fall and pruning residues. The potential of agroforestry to control both ordinary weeds and parasitic weeds had been well demonstrated by earlier researchers. A study conducted on hedge row intercropping system proved that weed numbers were reduced drastically in mulched plots compared to un-mulched plots. However, only limited studies were made in this direction, and further studies are needed to better understand the complex mechanisms in reducing weed population under different agroforestry practices in tropics.

6 Livelihood Securities and Other Services of Agroforestry

The agroforestry systems play indispensable role in enhancing farm income from diversified components, namely, crop, tree, and animal, at different intervals (Nair et al. 2009). Besides crop commodities, trees provide a variety of wood and non-wood products under agroforestry practices. In addition to timber and firewood, the leaves, fruits, nuts, seeds, livestock, and livestock products also generate substantial amount of income to farmers. Agroforestry systems in developing countries shall ensure the farmers are gaining additional economic benefits of C sequestration by C trading with developed countries under CDM projects (Nair et al. 2009). It will help the farmers to improve their farm economy besides securing environmental benefits to global communities. Policy analysis has shown that at prices of $100 per Mg C, carbon sequestration in agroforestry systems would have the potential to raise per capita incomes of farmers by up to 15% (Antle et al. 2007). However, it depends on the willingness of the farmers to adopt these potential tree-based land-use practices.

7 Conclusions

The anthropogenic activities are alarmingly increasing the concentrations of CO_2 in the atmosphere leading to the climate change. Agriculture ecosystem especially tropical agriculture is most vulnerable to climate change posing a serious threat on food production, nutritional security, and livelihoods of poor farming communities in developing countries (Verchot et al. 2007; Nath and Behera 2011; Murthy et al. 2013; Luedeling et al. 2014). Developing mitigation and adaptation strategies to minimize negative impacts of climate change on ecosystems has prompted a renewed interest in establishing promising tree-based alternate land-use systems. Agroforestry technologies have tremendous potentials in supplying diverse products as well as sequestering significant amount of C in degraded agroecosystems (Chauhan et al. 2011). Agroforestry technologies indeed offer viable opportunity to mitigate the atmospheric accumulation of CO_2 and other greenhouse gases and potential for transforming into resilient farming systems and help the farmers in adapting to climate change in tropics (Jose 2009; Yadava 2010). The degree of mitigation and adaptation varies according to the structural and functional complexities of systems. Some agroforestry systems also act as sources of GHGs, which could be reduced by judicious integration of components and their management. Burning, frequent tillage, and excessive use of agrochemicals shall be avoided. The agroforestry practices further facilitate better adaptation to adverse climate changes by ameliorating the microclimate, reducing the incidences of pests and diseases, and controlling weed population and cover the risks associated in crop failure. The beneficial effects of mulching, sheltering, and shading could be further exploited under agroforestry to minimize the risks of climate change.

Agroforestry systems in developing countries shall ensure the farmers in gaining additional economic benefits of C sequestration by C trading with developed countries under CDM projects. It will help the farmers to improve their farm economy besides securing environmental benefits to global communities (Antle et al. 2007). However, it is largely depending on the willingness of the farmers to adopt these potential tree-based land-use practices and policies of states to promote climate-resilient farming systems. The development of sustainable agroforestry system technologies is vital to achieve resilience in agroecosystems by linking mitigation and adaptation strategies to secure food production, livelihoods, economy, and unemployment in climate change scenarios in tropics (Jat et al. 2016). The current understanding of the potential of agroforestry to contribute to mitigation and adaptation to climate change is rather limited, and still a lot of research is needed for better understanding the role of agroforestry in buffering climate extremities in diverse socioeconomic and environmental setups in tropics.

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Chapter 30
Profiling Carbon Storage/Stocks of Cocoa Agroforests in the Forest Landscape of Southern Cameroon

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Abstract Despite evidence that cocoa agroforests are composed of different types of associated plants leading to varieties of structures, few studies have been done to assess the implications of these variations on carbon stocks. The current studies profile the carbon storage of cocoa agroforests in Southern Cameroon by: (1) evaluating the carbon stocks of cocoa agroforests in different ecological zones (Yaoundé, Mbalmayo, and Ebolowa), (2) evaluating the carbon stocks of cocoa agroforests under different management methods, (3) evaluating the contribution of some plant species to carbon sequestration inside cocoa agroforests, and (4) identifying the carbon stocks of some important species. Inside the cocoa agroforests of Southern Cameroon, associated plants store around 70% of the carbon. Cocoa agroforests with timber and NWFP (Non-Wood Forest Products) store more than twice what is found in systems rich with Musa and oil palm. In these systems, timber and NWFP store more than 2.5 times what is found in cocoa systems with high densities of cocoa, and such systems with timber and NWFP store more than 3.3 times the carbon of unshaded cocoa orchards.

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Among the companion plants, high value timber and edible NWFP contribute, respectively, to 30% and 10% of carbon storage by plants associated with cocoa. While the top ten plant species generally store more than half of what is found in associated plants, none of the species (except *Terminalia superba* in the Yaoundé Region) store more than 10% of what is found in associated plants. The proximity to market or remoteness and closeness to forest impact on this percentage. Using cocoa agroforests for climate change mitigation needs to take in consideration the utility and management of associated plants. In this perspective of climate change mitigation, beside biodiversity conservation, other co-benefits mainly related to the livelihood provided by cocoa agroforests need to be taken into consideration.

Keywords Cocoa agroforest · Carbon stock · NWFP · Timber · Cacao · Climate change mitigation · REDD+ · Forest landscape

1 Introduction

In forest and cocoa landscapes, the ecological importance of cocoa farming is becoming a subject of intense attention (Harvey et al. 2006; Schroth et al. 2004; Rice and Greenberg 2000; Gockowski and Sonwa 2011). Cocoa agroforests are seen as being useful for fulfilling some ecological services such as biodiversity conservation and helping to mitigate climate change. In addition to cocoa bean production fulfilling the needs of farmers and providing material for the chocolate industry, the cocoa farm is expected to fulfil some ecological services. In West and Central Africa, a few researchers are beginning to evaluate the ecological services expected from cocoa agroforests/orchards. Because of emerging results, cocoa is being gradually seen as being able to store some of the biodiversity of the forest, provide a buffer for protected areas, and at the same time fulfil some of the household needs of small holder farmers in forest landscapes (Gockowski and Dury 1999; Gockowski et al. 2004b; Sonwa 2004; Sonwa et al. 2000, 2001, 2002, 2003, 2010, 2014). The ability of cocoa agroforests to fulfil biodiversity conservation and household needs depends on the composition of the agroforest. Such composition was recently seen to be under the influence of several factors such as remoteness, access to market, and economical context (Sonwa et al. 2007). Responding to the international agenda of working toward more sustainable economies, chocolate industries are moving towards a deforestation-free value chain. This has led to a certification scheme being promoted in West and Central Africa (Waarts et al. 2013). Many of these certifications are aiming to make sure that a certain number of trees are kept in cocoa farms (Ingram et al. 2014). This will probably have an impact on cocoa farm composition.

From the perspective of using cocoa farms in climate-mitigation responses (such as REDD+ process: Reduced Emissions from Deforestation and Forest Degradation and conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries), carbon stocks have been evaluated in cocoa systems. Several studies have been conducted in West and Central Africa on carbon stocks (Oke and Olatiilu (2011); Gockowski and Sonwa 2011). These studies generally include assessment of carbon stocks in cocoa agroforestry systems. In some cases, the cocoa system is compared to a forest of the same landscape. These studies generally conclude that there is a decrease in carbon storage as we move from forest to cocoa agroforestry system (Zapfack et al. 2002). When compared to mixed food crops, it is generally observed that cocoa agroforestry systems store more carbon (ASB 2000).

Despite the variation in tree composition and structure in cocoa agroforests (Sonwa 2004; Sonwa et al. 2007, 2016) as we move from one part of the landscape to another, few studies have been conducted to understand the implication on carbon storage. While it is evident that cocoa agroforests result from the transformation of a forest (secondary/climax) to an agroforestry system by introduction and/or management of trees (Sonwa 2004; Sonwa et al. 2016), some recent studies are starting to mention the influence of certain types of trees on the carbon stock proportion of these forests. Big trees are being observed to be an important contributor to the carbon stocks in forests of Central Africa (Bastin et al. 2015). With the management of cocoa agroforests, repartition of class diameter is also affected and probably contributes to carbon storage. With the debate on co-benefits taking place within the UNFCCC (United Nations Framework Convention on Climate Change), it is evident that the multiple functions of cocoa agroforests will be at the center of efforts to respond to climate change, fulfil biodiversity conservation objectives, and reach the SDG (Sustainable Development Goals). In this context, the key question is what are the contributions of different types of trees (NWFP, timber, medicinal plants, etc.) to the storage of carbon. In view of filling these gaps, the current study profiles carbon storage of the cocoa agroforests of Southern Cameroon by: (1) evaluating the carbon stocks of cocoa agroforests in different ecological zones (Yaoundé; Mbalmayo and Ebolowa), (2) evaluating the carbon stocks of cocoa agroforests under different management methods, (3) evaluating the contribution of some plant species in carbon sequestration inside cocoa agroforests, and (4) identifying the carbon stocks of some important species.

2 Material and Methods

The study was carried out within the Alternative to Slash and Burn (ASB) framework in which site selection and methodology had been developed for making comparisons within a country but also with other sites located in the tropics (ASB 2000; Palm et al. 2004). The study was carried out within the first decade of the ASB program. We thus kept the same framework and methodologies developed during this period.

2.1 Study Site and Field Selection

The southern part of Cameroon is largely an evergreen forest and has been described in previous studies (see Sonwa et al. 2007, 2016). It constitutes an important part of the Congo Basin. The vegetation is rich and the wildlife diverse. Logging is very common in the area and has already caused serious degradation/deforestation. The forests of Southern Cameroon provide health and nutrient products to farmers, NWFP for the market, and land for farming. The southern Cameroon forest has been chosen as an experimentation site for the Congo Basin within the global effort to find technological interventions and policy recommendations for the ASB program (ASB 2000; Gockowski et al. 2004a). For this purpose, a benchmark of 1.54 M ha was designed (Fig. 30.1). This benchmark spans a gradient of population densities and encompasses significant special variations in market access, soils, and

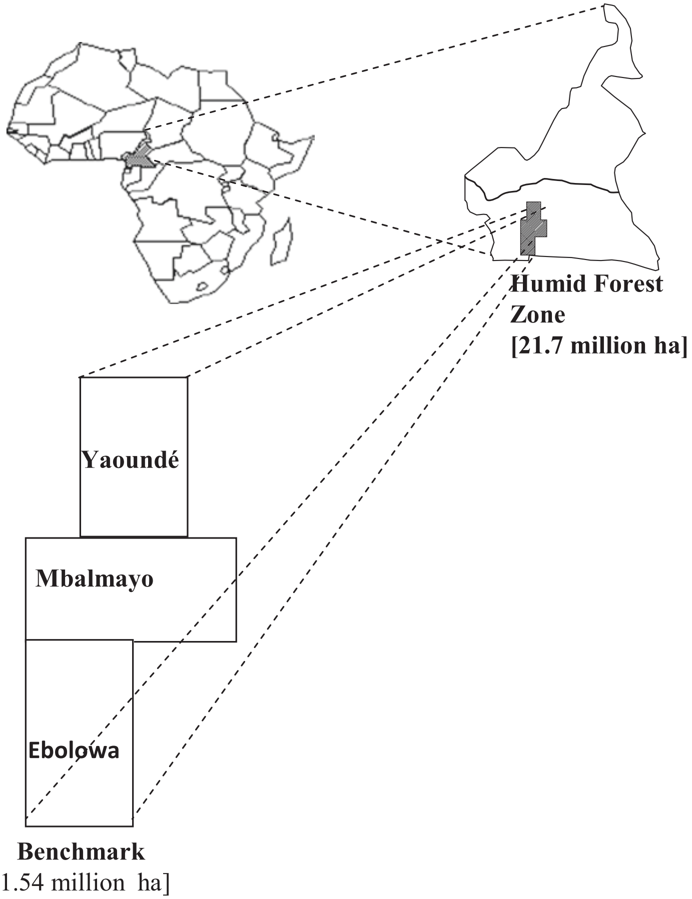

Fig. 30.1 Study site: the benchmark area of southern Cameroon

climate. The primary forest still covers 3.7% of land around Yaoundé, 5.3% around Mbalmayo, and 22% around Ebolowa (Thenkbail 1999).

Annual rainfall ranges from 1350 mm to 1900 mm and falls in a bimodal pattern. The soils of the region fall mainly into the broad FAO soil class of Orthic Ferralsols. Across the benchmark, 24.8% of the total surface area is estimated to be under agricultural use (including fallow fields). Cocoa occupies 3.8% of total land area representing 48% of the total productive agricultural land use. Over 100,000 ha of fallow land is cleared annually to create crop fields representing 3.8% of total land area. Mixed farming is predominant with groundnut-cassava- and melon-plantain-based systems. Food crops are mainly grown to meet subsistence needs. Cocoa is the primary source of income and there is still significant dependence on natural resources such as bush meat and gathering of NWFP. Previous studies in cocoa agroforests have shown that plant diversity within cocoa reduces as we move from Ebolowa (southern part of the landscape close to the forest) to Yaoundé (Sonwa et al. 2007). A recent study has also shown that the structure of cocoa agroforests changes as we move from Ebolowa to Yaoundé (Sonwa et al. 2016). In the Yaoundé area, the lower strata of the cocoa plantations tend to be denser and are used to grow plants that can easily be sold to the urban area. Around Yaoundé, some differences can be found within cocoa agroforests (Sonwa et al. 2010). Another important variation is what is found within cocoa plantations (Sonwa 2004). A closer look reveals that two Big categories of cocoa plantations can be identified in southern Cameroon: (i) with more cocoa trees and (ii) with less cocoa trees compensated by either NWFP and timber or oil palm and banana (Sonwa et al. 2016).

Two sets of sites were retained for the study. The first one was on the entire benchmark. The study was conducted in 12 villages, with five cocoa plantations per village. Vegetation data were thus collected in 60 plantations throughout the benchmark area (see Sonwa et al. 2007, 2016). The main aim here was to study the carbon storage in the entire Southern Cameroon.

The second aim of the experiment was to study carbon storage between different types of cocoa plantations. The objective of this part was to make comparisons among different types of cocoa and under different socio-ecological conditions. Previous work (Sonwa et al. 2016) related to the survey within 60 cocoa fields revealed the existence of three types of cocoa plantations in Southern Cameroon: Type A with a high density of banana plants and palm trees; Type B with a cocoa tree density 70% higher than the others; and Type C with a high density of high-economic value industrial timber together with non-timber forest products. It was difficult to have all the cocoa tree types within all the 12 villages of the benchmark previously selected. Some villages such as Awae had all three types. As Awae is in the Mbalmayo block (representing the intermediate situation between the degraded vegetation of the easily accessible part of the Yaoundé block on the one hand, and the mostly isolated, although less degraded, part of the Ebolowa block, on the other hand) we retained this village for a comparison between all three types. We further included the carbon storage of unshaded cocoa plantations under full sun cocoa systems in the context of Southern Cameroon.

2.2 *Data Collection and Carbon Stock Calculation*

2.2.1 Vegetation Composition and Structure

For each cocoa farm, the surface retained for the survey was 25% of the entire plantation. Elementary plots of 25 m × 25 m were used as subsurface areas for the survey. All the trees (cocoa and non-cocoa) with a diameter at breast height (dbh: diameter at 1.3 m) > 2.5 cm were recorded for all the plots. For each tree, the height was estimated and the species identified using the work of Vivien and Faure (1985, 1996) and Letouzey (1982), and comparisons were made with the specimen of the National Herbarium, Yaoundé. The main uses of the tree species were also noted through interaction with key informants. The species were then grouped into one of the following classes: edible, medicinal, timber, and others (see Sonwa et al. 2007, 2016).

2.2.2 Soil Sampling

Two sets of soil samples were collected: the first concerned the 60 plantations where the vegetation data was gathered. In each cocoa plantation soil was collected during the months of October and November, at a depth of 0–20 cm, at 24 point locations per cocoa farm, and mixed as one composite sample per cocoa plantation. The second set concerned soil samples from different transects selected for the study of differences between cocoa types (see Sonwa et al. 2016). In this set, soil samples were collected at a depth of 0–20 cm from ten points in each transect during the month of November.

For each cocoa plantation and transect, the soil was dried at 65 °C and mudded, and a 20-g sample was taken for lab analysis to analyze organic matter. The chemical analysis was done in the IITA lab in Yaounde-Cameroon.

2.2.3 Phytomass in Cocoa Agroforests

Above-ground biomass was calculated using the Brown allometric approach (1997) with application of the equation for the moist life zones based on diameter expressed as follows: $Y = 42.69–12.800(D) + 1.242(D^2)$ (where Y is in kg tree^{-1} and D the dbh in cm). For banana, the Arifin allometric approach (2001) was followed ($Y = 0.0303D^{2.1345}$, where Y is kg plant^{-1} and D in cm). Oil palm biomass was calculated using the formula of Frangi and Lugo 1985: [Y (biomass, kg) = 10.0 + 6.4 × total height (m); $n = 25$, $r^2 = 0.96$].

The above-ground phytomass for cocoa and non-cocoa trees within each of the 60 agroforests was calculated by computing the biomass of all the above plants and expressed as Mg biomass per ha. From this data (at the level of each cocoa plantation) the average above-ground phytomass (in Mg per hectare) was calculated for each block of the benchmark and the entire HFZ.

Root biomass was estimated using the shoot root ratio. Previous research in the same area (on five cocoa agroforestry plantations and six "primary and old secondary forests") for carbon stocks (Kotto same et al. 1997; Nolte et al. 2001) was useful, using the biomass of roots and shoots to obtain an estimate of the shoot/root ratio. The result of the simple regression was as follows—for the cocoa agroforestry system: root biomass = 0.138757 × tree biomass (kg)

$$\left(r^2 = 58.9571,\ p = 0.0746\right)$$

For "primary and old secondary forests": root biomass = 0.100991 × tree biomass

$$\left(r^2 = 98.3632,\ p = 0.0001\right)$$

As the value of the forest was not far from the lower bound of the root/shoot ratio in Cairns et al. (1997) to be conservative, we took 0.1 as the root/shoot ratio for this study.

Weed biomass was calculated using the weight of 20 samples collected in each cocoa plantation. Biomass was expressed in tons per hectare.

Ground biomass was calculated by pooling all the components for each of 20 points sampled per cocoa plantation. This was expressed in tons per hectare.

2.2.4 Carbon Stocks in Cocoa Agroforests

Above-ground carbon pools were measured for plants, understorey (weed), and surface litter based on their dry matter biomass by multiplying biomass by a factor of 0.45 (Nolte et al. 2001). Root carbon was evaluated by multiplying the root biomass by a factor of 0.45. We used the phytomass data obtained above to make the calculation.

Soil carbon per ha was determined by modifying the MacDicken formula (1997) originally made for 0–30 cm and applying it to the 0- to 20-cm soil sampled. The formula used was then: Soil C ha^{-1} = Organic C (percent C) × Bulk density (g cm^{-3}) 2000 × kg m^{-2}. We used the organic C analysis during this study (see Sect. 2.2.2). For the bulk density, we used the average value of 1.29 obtained in the benchmark by ASB (2000) between 0 and 15 cm soil inside cocoa agroforests of Southern Cameroon.

Total carbon stock of the system was the summation of carbon present in above-ground plant parts, roots, and soil carbon.

2.2.5 Statistical Analysis

All data were recorded in an Excel computer spreadsheet. The spreadsheet was imported into the Statgraphics statistical package. Each variable was subjected to ANOVA. Significantly different means were separated using the LSD (least significant difference) test. Means, LSDs, and the probability of the difference were entered in tables. Correlations between variables were conducted when necessary and results reported in the thesis. Data were analyzed as random complete blocks. No special transformation was made before statistical analysis.

3 Findings: Profile of Carbon Stocks in Complex Cocoa Agroforests

3.1 Carbon Stocks of Cocoa Agroforests in Different Ecological Zones

On average, a cocoa agroforest of Southern Cameroon can store 243 Mg ha^{-1} of carbon (Table 30.1). There is no difference between the 3 areas. Aboveground parts of plants associated with cocoa and cocoa trees, litter on the ground, and parts of the cocoa tree underground could store respectively 170, 13, 4, and 18 Mg of carbon ha^{-1}. The 37 Mg ha^{-1} stored in the soil accounts for 15% of all the carbon stock of the system.

3.2 Carbon Stocks in Different Cocoa Management Methods

The carbon stored in Type C agroforests (201 Mg ha^{-1}) is two to three times the amount stored in other cocoa management methods (Table 30.2). The above-ground parts of plants associated with cocoa stored 49, 39, and 147 Mg of carbon ha^{-1},

Table 30.1 Carbon stocks of cocoa agroforests in different ecological zones (Mg ha^{-1})

Zone	Carbon pool					Total
	Associated plants	Cocoa tree	Litter	Below ground	Soil	
Ebolowa	173 (71%)	11 b (4%)	4 (2%)	18 (8%)	38 (15%)	243 (100%)
Mbalmayo	170 (71%)	11 b (5%)	4 (2%)	18 (8%)	35 (15%)	238 (100%)
Yaoundé	168 (68%)	17 a (7%)	5 (2%)	19 (8%)	39 (16%)	247 (100%)
HFZ	170 (70%)	13 (5%)	4 (2%)	18 (8%)	37 (15%)	243 (100%)
P	0.10	0.00	0.36	0.10	0.48	0.98
LSD ($p \leq 0.05$)	79	4	1	8	6	88

Means not sharing a common letter in a column are significantly different at $p \leq 0.05$ probability
P Probability, *LSD* Least significant difference, *HFZ* Humid forest zone

Table 30.2 Carbon stocks of cocoa agroforest under different management methods (Mg ha^{-1})

Options	Carbon pool					Total
	Associated plants	Cocoa tree	Litter	Below ground	Soil	
Type A	49 b (52%)	10 b (10%)	3 b a (3%)	6 b (6%)	27 b (29%)	95 b (100%)
Type B	39 b (48%)	7 b (9%)	3 b (3%)	5 b (6%)	28 b (35%)	81 b (100%)
Type C	147 a (73%)	6 b (3%)	4 a (2%)	15 a (8%)	29 b (14%)	201 a (100%)
Type S	1 b (1%)	20 a (33%)	3 ab (5%)	2 b (3%)	35 a (58%)	60 b (100%)
P	0.01	0.00	0.06	0.01	0.00	0.02
LSD ($p \leq 0.05$)	78	4	1	8	4	87

Means not sharing a common letter in a column are significantly different at 0.05 probability
Type A: cocoa agroforest with high density of Musa spp. and oil palm plants; Type B: cocoa agroforest with high density of cocoa; Type C: cocoa agroforest with high density of timber and non-timber tree species; Type S: unshaded cocoa orchard
P Probability, *LSD* Least significant difference

respectively in types A, B, and C. In the absence of shade, the carbon stored in above-ground parts of the cocoa tree (20 Mg ha^{-1}) is two to three times the amount under shade conditions. Carbon stored in the soil is significantly ($p \leq 0.01$) high without shade.

Carbon stored in the above-ground parts of associated plants accounted for 50–75% of the carbon stock under different shade conditions. Carbon stored in the above-ground part of the cocoa tree accounted for 3–10% of the total carbon stored under shade conditions, against 33% when there is no shade. More than 50% of carbon stored is in the soil in unshaded cocoa plantations against 14–35% under shade conditions.

3.3 *Carbon Store in Different Classes/Uses of Plant Species Associated with Cocoa*

High-value timber stored 40.8 Mg carbon ha^{-1} and accounted for 25% of the total amount stored in the above-ground parts of plants associated with cocoa (Table 30.3). Medicinal plants stored on average 10.3 Mg ha^{-1}. Carbon stored by the above-ground parts of edible plants (i.e., exotic plants, NWFP, *Musa* spp., and oil palm) accounted for 15% of the carbon of plants associated with cocoa. Exotic plants stored 13.3 Mg carbon ha^{-1} around Yaoundé as opposed to 3.4 and 1.1, respectively, around Ebolowa and Mbalmayo. The carbon stored by edible NWFP around Yaoundé represented 40% of the amount stored by similar plants in Ebolowa and Mbalmayo.

Table 30.3 Carbon stored by plants associated with cocoa according to their main use (Mg ha^{-1})

Plant group	Ebolowa	Mbalmayo	Yaoundé	HFZ	P
Exotic edible	3.4 b (2.0%)	1.1 b (0.7%)	13.3 a (7.9%)	5.9 (3.5%)	0.00
Edible NWFP	22.0 a (12.8%)	20.7 a (12.6%)	8.3 b (5.0%)	17.0 (10.1%)	0.00
Banana	0.0 b (0.02%)	0.0 b (0.02%)	0.2 a (0.12%)	0.1 (0.05%)	0.02
Oil palm	0.1 b (0.03%)	0.0 b (0.02%)	0.1 a (0.07%)	0.1 (0.04%)	0.00
Medicinal plants	9.5 (5.5%)	12.3 (7.5%)	9.1 (5.4%)	10.3 (6.1%)	0.84
High value timber	46.6 (27.1%)	41.3 (25.1%)	61.8 (36.7%)	49.9 (29.7%)	0.78
Low value timber	46.4 (27.0%)	41.1 (25.0%)	35.0 (20.8%)	40.8 (24.3%)	0.87
Others	44.1 (25.6%)	47.6 (29.0%)	40.4 (24.0%)	44.0 (26.2%)	0.46
Total	172 (100%)	164 (100%)	168 (100%)	168 (100%)	0.97

Means not sharing a common letter in a column are significantly different at 0.05 probability
P probability, *HFZ* humid forest zone

3.4 Carbon Storage by Main Plant Species

Terminalia superba is among the plant species with a high carbon storage (14 Mg ha^{-1}) (Table 30.4). It is followed by *Ceiba pentandra*, *Pycnanthus angolensis, Ficus mucuso*, and *Triplochiton scleroxylon*. Trees from each of these species stored more than 9 Mg carbon ha^{-1}, accounting for more than 5% of the carbon in above-ground parts of the plants associated with cocoa. *Aelstonia boonei, Pentaclethra macrophylla, Spathodea campanulate*, and *Petersianthus macrocarpus* stored around 6–8 Mg carbon ha^{-1}.

The top ten species stored generally more than 50% of carbon held by associated plants in each ecological area and in the entire area.

4 Discsussion

The total carbon stock of 243 Mg ha^{-1} is less than the 308 Mg ha^{-1} of the primary forest of Southern Cameroon (Kotto Same et al. 1997), but is higher than the 137.70 and 228.32 Mg ha^{-1} obtained in the ASB study in Southern Cameroon (Nolte et al. 2001). In the study by Kotto Same et al. (1997), cocoa agroforests account for 62% of the carbon stock of the primary forest.

A recent review study shows that conversion from forest to cocoa generally leads to a loss of carbon stock (Obeng and Agullar 2015). In Nigeria, Oke and Olatiilu (2011) observed that 10 years after conversion of primary forest to sparse and dense cocoa, the losses of above-ground carbon stock were 89.82% and 71.20%, respectively. In South-East Ghana, natural forest contains 304.8 Mg ha^{-1} versus 266.2 Mg ha^{-1} in cocoa agroforests, implying that cocoa agroforests were storing 87.33% of the carbon of primary forests. In Cameroon, Saj et al. (2013) observed that the forest tree component, before the establishment of cocoa plantation, significantly affected density of plants in cocoa plantation. However, the values she obtained were very

Table 30.4 Carbon stock of the top ten plant species associated with cocoa in Southern Cameroon (Mg ha^{-1})

	Species	Ebolowa	Mbalmayo	Yaoundé	HFZ
1	*Terminalia superba*	4.8 (2.8%)	14.1 (8.6%)	23.9 (14.2%)	13.9 (8.3%)
2	*Ceiba pentandra*	11.5 (6.7%)	9.6 (5.9%)	14.2 (8.4%)	11.7 (7.0%)
3	*Pycnanthus angolensis*	18.0 (10.4%)	7.7 (4.7%)	8.2 (4.9%)	11.4 (6.8%)
4	*Ficus mucuso*	*12.5* (7.3%)	*15.1* (9.2%)		*11.3* (6.7%)
5	*Albizia adianthifolia*		7.9 (4.8%)	16.0 (9.5%)	9.2 (5.5%)
6	*Triplochiton scleroxylon*	13.1 (7.6%)		10.3 (6.1%)	9.1 (5.4%)
7	*Alstonia boonei*	12.8 (7.4%)	5.9 (3.6%)		7.8 (4.6%)
8	*Pentaclethra macrophylla*		10.3 (6.3%)	7.6 (4.5%)	7.2 (4.3%)
9	*Spathodea campanulata*			13.4 (7.9%)	6.3 (3.7%)
10	*Petersianthus macrocarpus*	7.1 (4.1%)	5.8 (3.5%)		6.0 (3.6%)
12	*Albizia glaberrima*	9.4 (5.4%)			
13	*Pterocarpus soyauxii*	5.7 (3.3%)			
14	*Millicia excelsa*	5.3 (3.1%)	4.5 (2.8%)		
15	*Trilepisium madagascariense*		6.6 (4.0%)		
16	*Albizia zygia*			7.6 (4.5%)	
17	*Persea americana*			9.1 (5.4%)	
18	*Mangifera indica*			7.7 (4.6%)	
	Total of the top 10 plant	100 (58%)	87.5 (53%)	117.9 (70%)	94 (56%)
	Total	173 (100%)	170 (100%)	168 (100%)	170 (100%)

HFZ humid forest zone

low (about 30%) compared to previous studies. Kotto-Same et al. 1997 observed that transforming a mixed cropping system to a cocoa field will lead to a carbon stock increase of 91 Mg ha^{-1}. Land use management from the perspective of climate change mitigation will tend to move toward a system that stores more carbon. The Type C agroforests with more NWFP and timber will be more appropriate for carbon storage.

Within cocoa plantations, the more NWFP and timber the system contains as associated plants (Type C), the larger the above-ground biomass. Increasing the number of cocoa trees does not increase biomass. Removal of shade reduces carbon stock by threefold compared to the amount found in the system with more NWFP and Timber. Associated plants are the main pool of biomass. A few of these plants, mainly timber, play a key role in carbon stock. Proper management of the carbon pool will go hand in hand with good management of the latter species in the system.

Soil carbon in the study area accounted for 15% of the total carbon stock and did not vary as we moved from the one landscape to another (335–39 Mg ha^{-1}). In the southeast of Ghana, soil (0–15 cm) accounts for 8.1% (15 Mg ha^{-1}) of total carbon stock. It was observed that the removal of shade tends to increase the amount of carbon stock in the soil of Southern Cameroon. Norgrove and Hauser (2013) found no difference between carbon stocks in the soil under forests and shade cocoa agroforest systems within 0–100 cm. Kotto-Same et al. (1997) found the soil carbon pool to be the most stable in forest landscapes. Despite changes in above-ground carbon stocks between cocoa agroforest systems, the soil carbon tends to be unchanged. The removal of shade increases the carbon stock of cocoa trees. The system with more NWFP and timber tends to have more litter. This could be explained by more leaf falling from trees present within the cocoa agroforest. The difference between above-ground forests and cocoa agroforests and different types of cocoa agroforest, as is the case in this study, suggests that this carbon pool needs to be properly monitored during the management of cocoa agroforests.

Generally, the top ten plant species contribute to more than 50% of carbon storage of plants associated with cocoa. This percentage was 70% near Yaoundé, suggesting that an important pool of carbon is stored in well-known species. For example, timber trees are supposed to be felled when their diameter is large enough to be cut by logging companies or small-holder loggers. Robiglio et al. (2013) have already noticed that in Southern Cameroon, the main component (13%) of trees felled by small holders around Yaoundé were from cocoa plantations.

5 Conclusion

A cocoa agroforest of Southern Cameroon stored on average 243 Mg of carbon ha^{-1}. Above-ground parts of the plants associated with cocoa accounted for 70% of the carbon storage while cocoa trees accounted only for 5%. Concerning carbon stored by associated plants, edible species accounted for 15%, while medicinal plants accounted for 6% and high value timber for 25%. Some trees including *Terminalia superba* contributed highly to the storage of carbon. Cocoa associated with NWFP and HVT stored two to three times more carbon than other management systems. Removing shade contributes to increased carbon stock of cocoa trees. This suggests that associated plants not only contribute to shade but also increase the capacity of farms to store carbon. Since those plants provided structure similar to that of forests, their products (timber, NWFP, medicinal plants, etc.) and services (e.g., biodiversity conservation) will appear as co-benefits of cocoa agroforestry on top of carbon storage.

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Chapter 31
Bioenergy in India: Status, Policies and Prospects

M. M. Roy and Sharmila Roy

Abstract There is a trend all over the world for increased use of bioenergy on account of almost carbon-neutral nature. The global estimates suggest that almost half of new generation capacity in context of energy in the coming years will be either from biomass or the nuclear one. In Indian context, promotion of biomass and waste-based energy is becoming very relevant from the viewpoints of green energy, recycling of wastes and cleanliness. The estimated potential of present biomass-based energy in the country is over 25,000 MW, and the installed production capacity is 5941 MW. Thus, there is great scope to realize the actual potential of bioenergy through adoption of enabling policies and supporting mechanisms. Various categories of biomass and waste availability and present status of bioenergy production in the country are presented. The challenges, policies and future prospects in this context are discussed.

Keywords Bioenergy · Bagasse · Biodiesel · Biofuel · Biogas · Energy plantation · Sugarcane wastes

1 Introduction

Because of the growing concerns of global warming, the interest in promotion of bioenergy is rising in developed and developing countries. In fact, biomass-based energy is close to 'carbon neutral' – producing energy while only releasing carbon to the atmosphere that has been captured during the growing cycle of the plant, rather than emitting carbon that has been locked away from the atmosphere in fossil reserves for millions of years (Ravindranath and Hall 1995). The contribution of biomass energy towards total primary energy consumption varies from 15 to 38% in various countries. It provides basic energy requirements for cooking and heating of

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rural households and for heating process in a variety of traditional industries. Unlike solar and wind, biomass is relatively a much reliable source of energy free of fluctuations and does not need storage as in case of solar energy. However, it has not yet emerged as the preferred energy source, mainly on account of challenges involved in ensuring reliable biomass supply chain (Hegazy 2013; TERI 2016).

In ancient India, biomass energy consumption has been a practice in the form of cow dung cake, firewood, husk and a variety of other natural feedstocks. A great deal of technological improvement has also taken place for their safer and more efficient usage (Pachauri and Jiang 2008). India is home to 18% of world's population and uses only 6% of the world's primary energy. Presently conventional sources (thermal based on coal, natural gas and oil) constitute bulk of requirement (68%), followed by hydropower (18%), new and renewable energy (12%) and nuclear energy (2%). The energy consumption in the country has doubled since 2000, and the potential for further rapid growth is enormous (IEA 2015). The power demand is increasing in rural parts of the country. The likely huge requirement for power will necessarily require increased focus on biomass energy as well (Balachandra 2011). As per IEA (2015) estimates, more than over 50% of new generation capacity will come from renewables and nuclear. In this paper, various categories of biomass that are used or could be used as a source of biomass energy in India are reviewed. The present status of biomass power in the country and future prospects is presented. The points related to enabling policies in promotion of bioenergy in India are outlined.

2 Bioenergy Resources

Bioenergy is the most widely used renewable energy worldwide and is defined as 'energy contained in living or recently living biological organisms' (fossil fuels are thus excluded). This can be differentiated into biofuel, biogas and solid biomass. Biomass is organic matter derived from living or recently living organisms that can be used as source of energy and most often refers to as plant-based materials, specifically lingocellulosic matter (Klass 1998). The major sources of biomass that may lead to generation of energy in India are presented in Table 31.1 and Fig. 31.1. Such resources consists of different kinds of wastes and by-products besides fast-growing tree species used as fuel in energy plantations.

2.1 Energy Plantations

Energy plantation means growing select species of trees/shrubs which are harvestable in a shorter time and are specifically meant for fuel. The fuel wood may be used either directly in wood burning stoves and boilers or processed into methanol, ethanol and producer gas. These plantations help provide wood either for cooking in homes or for industrial use, so as to satisfy local energy needs in a decentralized

Table 31.1 Listing of major sources for biomass in India

Source	Description
1. Energy plantations	Trees grown on marginal lands for supplying wood for generation of energy. Notable examples include *Prosopis juliflora*, *Leucaena leucocephala*, etc.
2. Wastes	
2a. Agricultural waste	The range includes straws of cereals and pulses, cobs, rice husks, sugarcane trash, stalks of fibre crops, seed coats of oil seeds, oil cakes, coconut shell, etc.
2b. Forest waste	Wood, stubbles, leaf litter, dead seeds and spores, etc. Forest industry-based product like saw dust, etc.
2c. Agro-industrial waste	The range includes textile fibres, bagasse and molasses from sugar mills, pulp wastes from food processing units, wastes from paper mills, etc.
2d. Municipal solid waste	Food and kitchen wastes, green waste, paper, inert wastes like fabrics, clothes, etc.

Fig. 31.1 Top left, utilization of rice straw is possible as animal feed and industrial use, including power generation; bottom left, view of a 12 MW biomass power plant in India that may utilize rice straw and other crop residues; top right, harvesting of *Prosopis juliflora* wood for domestic fuel use and also to feed biomass power plants in Rajasthan; bottom right, full view of a 10 MW biomass power plant (Transtech Green Power Limited) based on *Prosopis juliflora* and other wood wastes in Sanchore district (Rajasthan)

manner. The merits of energy plantations are (a) heat content of wood is similar to that of Indian coal; (b) wood is low in sulphur and not likely to pollute the atmosphere; (c) ash from burnt wood is a valuable fertilizer; (d) utilization of erosion prone land for raising these plantations helps to reduce wind and water erosion, thereby minimizing hazards from floods, siltation and loss of nitrogen and minerals from soil; (e) help in rural employment generation – it is estimated that 1 ha of energy plantation is estimated to provide employment for at least seven persons on a regular basis; (f) the plantations provide a number of by-products like oils, organic compounds, fruits, edible leaves, forage for livestock, etc. (Pandey 2002).

Fast-growing species like *Azadirachta indica*, *Prosopis juliflora*, *Leucaena leucocephala*, *Melia dubia* and bamboo are usually preferred in such plantation programs. There has been research to identify better fuel wood trees based on the calorific value of the wood and other such parameters like fuel value index (FVI) (Jain 1992; Kumar et al. 2009). In energy plantation, projects such as trees may be given appropriate weightage.

2.2 The Wastes

The wastes are unwanted or unusable material. These are any substance which is discarded after primary use or are worthless, defective and of no use. Therefore, using waste as a source of energy is a good way to dispose or process it, producing energy on the way. There are several benifits of bioenergy derived from wastes, viz. environment-friendly nature, potential source for local employment, by-product usage as fertilizer, etc., as one solution to the substitution of oil (IISC 2004; WEB 2012).

2.2.1 Crop Residues

A diverse kind of biomass is available from farmlands in the country. Agricultural residues from many crops (>50) are used for biomass power. Their potential availability is presented in Table 31.2. The use of crop residues varies from region to region based on requirements of the region and characteristics of the residue in the form of calorific value, lignin content, density, palatability, nutritive value, etc. (Hiloidhari et al. 2014). Conversion of such residue to bioenergy is either thermochemical (gasification/pyrolysis) or biochemical (biogas). The resulting fuel may be solid, liquid or gas. There are good prospects of utilizing abundant crop residues such as paddy which do not compete for use as animal feed for fuel purposes (Baruah and Jain 1998; Murali et al. 2007).

Because of the high animal population in the country, there is a good prospect of their utilization in the form of dung and other animal waste materials for fuel and energy generation purposes. It also serves as good manure and as cement for poor man in construction activity. About 37% of total wet dung production in the country is utilized for fuel, 60% as manure and 3% as plastering of mud houses (Dikshit and Birthal 2010).

Table 31.2 Potential availability of bio-feedstocks for power generation in India

Crop	Residues	Biomass potential ($\times$1000 Mg year^{-1})
Paddy	Straw, husk, stalks	169,965
Wheat	Stalks, panicles	112,034
Cotton	Stalk, husk, boll shell	52,937
Maize	Stalk, cobs	26,958
Jowar	Cobs, stalk, husk	24,208
Bajra	Stalk, cobs, hub	15,832
Groundnut	Shell, stalk	15,120
Sugarcane	Tops, leaves	12,144
Banana	Miscellaneous residues	11,937
Coconut	Fonds, husk, pitch, shell	10,464
Soya bean	Stalks	9940
Mustard	Stalks, husk	8657
Arhar	Stalks, husk	5735
Gram	Stalk	5441
Other crops (# 44)	Miscellaneous residues	29,669

Source: Adapted from Kumar et al. (2015)

As per GoI (2011) estimates based on the availability of cattle dung alone, a potential of about 18,240 million m^3 of biogas generation exists in India. Also, poultry excreta from bird population may add to 2173 million m^3 of biogas.

2.2.2 Agro-industrial Waste

Such wastes include wastes from paper mills, pulp wastes from food processing industries, textile fibre wastes, molasses from sugar industry, whey from dairy plants, etc. There are some studies that estimate their potential for generating and capturing methane from agro-industrial waste for use as fuel in India. The national master plan (NMP) for the development of waste to energy in industrial sectors covers sectors like distilleries, dairy farms and milk processing plants, paper and pulp production, poultry farms, tanneries, slaughter houses, cattle farms, sugarcane processing, corn starch production and tapioca production (GMI 2011).

2.2.3 Forest Waste

Such wastes include leaves, barks, logs, chips and forest industry-based products like saw wood. The concept of forest-based bioenergy (FBE) is favoured in many countries through policies as it is an environment-friendly alternative to fossil fuels (FAO 2008). There is scanty information related to opportunities and challenges associated with use of forest wastes for bioenergy. However, dependency of rural people on forest biomass for cooking and heating is immense. So a scope exists to evaluate the benefits and challenges of such projects in India (Halder et al. 2014).

2.2.4 Municipal Solid Wastes

Municipal solid wastes (MSW) are significant in urban areas of the country. It consists of household waste, wastes from hotels and restaurants, construction and demolition debris, sanitation residue and wastes from streets. It is either in solid or semi-solid form. As per estimates, more than 55 million tons of MSW is generated in India annually. The yearly increase is about 5%. The biodegradable portion of MSW is quite significant in the country. The estimated energy recovery potential from municipal solid wastes is about 1500 MW based on 2002 and it could go up to 5200 MW in 2017 (Bhattacharya et al. 2005; EAI 2012).

3 Present Status

In India, biomass has always been an important energy source on account of multiple benefits it offers. About 32% of total primary energy is derived from biomass, and more than 70% of the population depends on it in some or the other way. For the power sector in the country, it is a carbon-neutral fuel source for generation of electricity, has the ability to provide much-needed relief from power shortages and generates employment in rural areas. As per estimates of GoI (2016), a great potential exists in the country for bioenergy through biomass (17,536 MW), cogeneration through bagasse (5000 MW) and utilization of wastes (2554 MW) (Table 31.3). However, the present capacity of biomass power sector is about 5941 MW that includes 4946 MW grid connected and remaining 995 MW as off-grid/captive power (Table 31.4).

3.1 Biomass-based Power Plants

The biomass power plants are based on a variety of agricultural wastes. Gasifier-based power plants provide off-grid decentralized power and are lighting homes in several Indian states. In case of grid-based power solution, 8–15 MW thermal biomass plants are feasible. Such energy is reliable free of fluctuations and storage is not needed. The potential and present installed capacity of commissioned biomass power (excluding cogeneration) in leading states of India is depicted in Table 31.5.

It is evident from the table that average biomass utilization in the country against the estimated potential is only 26.34%. States like Chhattisgarh and Uttarakhand, utilization is over 88%, while a great scope exists in states like Bihar, Haryana, Madhya Pradesh, Punjab, Gujarat, West Bengal, etc.

Table 31.3 Estimated potential of major types of bioenergy in India (in MW)

State/UT	Biomass power	Cogeneration bagasse	Waste to energy
Andhra Pradesh	578	300	123
Arunachal Pradesh	8	–	–
Assam	212	–	8
Bihar	619	300	73
Chandigarh	–	–	6
Chhattisgarh	236	–	24
Delhi	–	–	131
Goa	26	–	–
Gujarat	1221	350	112
Haryana	1333	350	24
Himachal Pradesh	142	–	2
Jammu & Kashmir	43	–	–
Jharkhand	90	–	10
Karnataka	1131	450	–
Kerala	1044	–	36
Madhya Pradesh	1364	–	78
Maharashtra	1887	1250	287
Manipur	13	–	2
Meghalaya	11	–	2
Mizoram	1	0	2
Nagaland	10	–	–
Odisha	246	0	22
Pondicherry	–	–	3
Punjab	3172	300	45
Rajasthan	1039	–	62
Sikkim	2	–	–
Tamil Nadu	1070	450	151
Tripura	3	0	2
Uttar Pradesh	1617	1250	176
Uttarakhand	24	–	5
West Bengal	396	1	148
Others	–	–	1022
All India	*17,536*	*5000*	*2554*

Source: GoI (2016)

3.2 *Bagasse and Cogeneration*

Bagasse is the fibrous matter that remains after sugarcane stalks are crushed to extract their juice. Such a by-product generated in the manufacture of sugar is used for generation of steam which in turn is used as a fuel source, and the surplus generation is exported to the power grids of state governments. Nearly 3 Mg of wet

Table 31.4 Present capacity of biomass power sector in India

Type	Capacity (MW)
Grid interactive	
Biomass power (combustion, gasification and bagasse cogeneration)	4831.33
Waste to power	115.08
Subtotal	4946.41
Off-grid/captive power	
Biomass (non-bagasse) cogeneration	651.91
Biomass gasifiers	
Rural	18.15
Industrial	164.24
Waste to energy	160.16
Subtotal	994.46
Total biomass	*5940.87*

Source: Biomass Knowledge Portal (2016)

Table 31.5 Installed capacity of commissioned biomass power (excluding cogeneration) projects in India

State/UT	Present capacity (MW)	Utilization (%)
Andhra Pradesh	217.2	37.58
Bihar	0.12	0.02
Chhattisgarh	209.9	88.56
Gujarat	56.3	4.61
Haryana	13.5	1.01
Karnataka	468.3	41.41
Madhya Pradesh	36	2.64
Maharashtra	531.88	28.19
Odisha	20	8.13
Punjab	93.5	2.95
Rajasthan	111.3	10.71
Tamil Nadu	335.3	31.34
Uttarakhand	20	88.33
Uttar Pradesh	219.27	13.56
West Bengal	26	6.57
Others	974.63	60.80
	3333.2	26.34

Source: Compiled using data from Biomass Knowledge Portal (2016) and GoI (2016)

bagasse (50% moisture) is produced for each 10 Mg of sugarcane crushed. The other uses of bagasse include manufacture of paper and pulp products and building materials (Paturau 1988). Ethanol is also produced from bagasse, which in turn can successfully be used as bioenergy.

The details of commissioned bagasse cogeneration projects in India are presented in Table 31.6. The country has the potential to generate 5000 MW of power through bagasse. The installed capacity is around 2334 MV (3123 MV in peak season) through 213 projects located in the sugar mills. After modernization of the sugar mills, future potential of power is expected to touch 5000 MW (Mishra et al. 2014).

It is evident from the table that average bagasse utilization in the country against the estimated potential is 46.64%. In states like Karnataka and Tamil Nadu, utilization is over 70%, while a great scope exists in states like Haryana, Bihar and Punjab.

3.3 Biogas

Biogas typically refers to a mixture of different gases produced by breakdown of organic matter in the absence of oxygen. It is primarily methane and carbon dioxide and may have small amounts of hydrogen sulphide, moisture and siloxanes. The energy released may be used as fuel for cooking and may be converted into heat and electricity. It can be compressed in the same way as natural gas is compressed to CNG and can serve as transportation fuel. The present status of biogas plant installed and production of biogas in leading ten states of India are presented in Table 31.7. The major states include Maharashtra, Andhra Pradesh, Karnataka, Gujarat, Uttar Pradesh, West Bengal, Assam, Madhya Pradesh, Tamil Nadu and Odisha.

The total production of biogas is estimated about 2075.7 million m^3 in the country during 2014–2015. This is equivalent to 66 million domestic LPG cylinders and equivalent to 5% of total LPG consumption of the country (Abhishek 2015). Now when viability and safety of energy alternatives are being debated, it is pertinent to look to biogas, one of the oldest means of renewable energy use.

Table 31.6 Details of commissioned bagasse cogeneration projects in India

State	Projects (#)	Installed capacity (MW)	Utilization (%)
Andhra Pradesh	22	163.55	54.35
Bihar	4	43.30	14.43
Haryana	4	31.80	9.09
Karnataka	32	403.88	89.75
Maharashtra	65	580.90	46.47
Punjab	6	62.00	20.67
Tamil Nadu	26	327.00	72.67
Uttar Pradesh	53	710.00	56.80
Uttarakhand	1	10	–
Total	213	2332.43	46.64

Source: Mishra et al. (2014)

Table 31.7 Present status of biogas plants, biomass gasifiers and production of biogas in leading states of India

States	Biogas plants (#)	# Biomass gasifiers (rural-industrial)	Biogas production (million cu m)
Maharashtra	843,011	7150	357.8
Andhra Pradesh	505,712	22,914	216.5
Karnataka	459,071	7447	198.5
Gujarat	426,374	21,530	196.5
Uttar Pradesh	435,554	23,702	169.3
West Bengal	366,018	26,168	146.0
Assam	102,302	2933	140.3
Madhya Pradesh	336,703	9008	137.0
Tamil Nadu	220,861	11,762	113.7
Odisha	260,056	270	101.2

Source: Compilation based on GoI (2013) and Abhishek (2015)

3.4 Ethanol and Biodiesel

A feedstock containing significant amounts of sugar or materials that can be converted into sugar (like starch or cellulose) is useful to produce ethanol (Fig. 31.2). The available ethanol in the biofuel market is based on either sugar or starch. The most common feedstock is sugarcane (Ralph et al. 2014). Such sugary biomass is fermented directly to ethanol. Other crops include sugar beet and to a lesser extent sweet sorghum. Common starchy feedstock includes maize, wheat and cassava (Matsuoka et al. 2014; Shaik and Kumar 2014).

India is the world's second largest sugarcane producer and a major manufacturer of molasses-derived ethanol. States of Uttar Pradesh, Maharashtra, Karnataka and Tamil Nadu contribute bulk (>80%) of it. Around 330 distilleries produce about 4 billion litre of rectified spirit (alcohol) per year. Of this about 160 distilleries have the capacity to distil around 2 billion litres of conventional ethanol per year. During the last decade, ethanol consumption grew from 1.8 billion litres to 2.4 billion litres. It is expected to increase about 2.5 billion litres in 2017. The likely consumption pattern is 700 million litres for fuel ethanol and 1.8 billion litres for the industrial and chemical sectors. The blend ratio is quite less than the government guidelines (Table 31.8).

Importance of biofuel is increasing in India because of reducing import expenses and its eco-friendly nature. The major feedstocks include molasses for production of ethanol and nonedible oilseeds like *Jatropha* and *Pongamia* for biodiesel (Fig. 31.3).

The other potential plants for biodiesel in the country include *Azadirachta indica* (neem), *Madhuca longifolia* (mahua) and other wild plants. The other feedstocks include unusable edible oil waste (used-once) and animal fats. The government plans

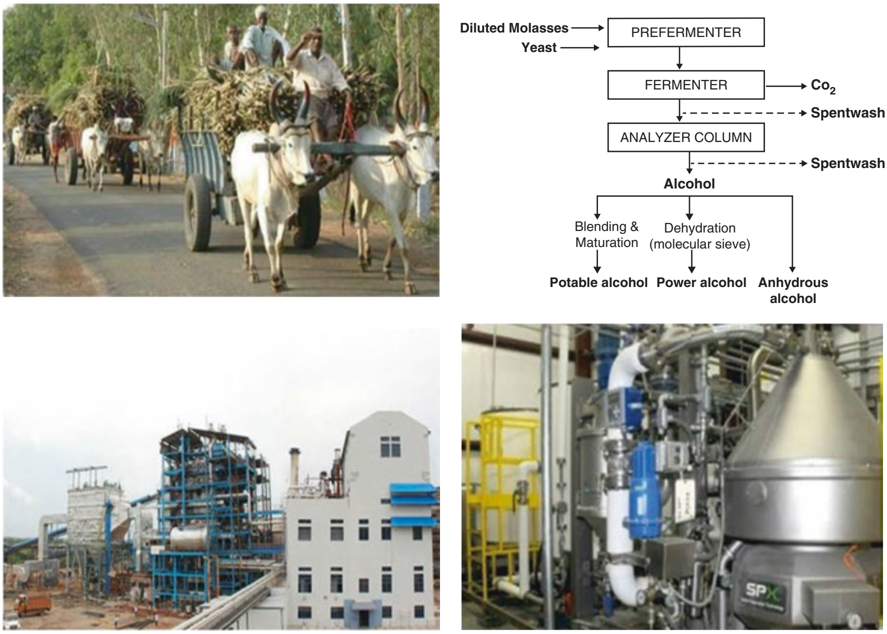

Fig. 31.2 Top left, harvested sugarcane is being transported to sugar mills for sugar production, cogeneration and bioethanol production; bottom left, full view of sugar mill in Maharashtra that houses a 30 MW bagasse cogeneration power plant; top right, scheme of bioethanol production from sugarcane molasses; bottom right, view of a bioethanol production unit in a sugar factory in India

Table 31.8 Patterns of consumption of ethanol as transport fuel in India (in billion litres)

Year	Consumption	Refineries (#)	Fuel use	Blend ratio
2010	1.76	115	0.005	0.3
2011	1.95	115	0.365	1.8
2012	2.04	115	0.305	1.4
2013	2.06	115	0.382	1.6
2014	2.3	115	0.350	1.4
2015	2.44	160	0.685	2.3

Source: GAIN (2016)

to meet up to 20% of country's diesel requirement through biodiesel route (Raju et al. 2012). However, the present pattern of biodiesel consumption is quite low.

Biodiesel is also used in brick kilns, cellular communication towers and diesel generators as source of power backup (Table 31.9).

Currently, India has five to six large capacity plants (10,000–250,000 megagram per year) and utilizes 28% of the installed capacity using multiple feedstocks such as inedible vegetable oils, unusable edible oil waste (used-once) and animal fats.

Fig. 31.3 Top left, plantation of *Jatropha curcas* in Chhattisgarh of ICBL company; bottom left, view of a biodiesel processing plant (30 MTPD) operating on a commercial scale; top right, view of a planation site of *Pongamia pinnata* in Maharashtra; middle right (left), seeds of *Jatropha curcas*; middle right (right), seeds of *Pongamia pinnata*; bottom right, biodiesel quality from a processing plant in West Bengal that surpasses the standards

Table 31.9 Patterns of consumption of biodiesel as transport fuel in India (in million litres)

Year	Consumption	Refineries (#)	Fuel use	Blend ratio
2010	52	5	26	0.06
2011	60	5	30	0.07
2012	70	5	35	0.07
2013	75	6	38	0.08
2014	80	6	40	0.08
2015	90	6	45	0.08

Source: GAIN (2016)

4 Policy Issues and Prospects

There has been a long history of bioenergy planning and program interventions in India. In 1970, points were suggested for biomass as a component of rural and renewable energy policies. This included improving efficiency of traditional biomass use; improving supply of biomass; technologies for improving quality of biomass use; introduction of biomass-based technologies, like gasifiers; and establishing institutional support for program formulation and implementation.

The earlier initiatives were National Project on Biogas Development (initiation 1981) with a view to set up family type biogas plants and National Programme on Improved Cookstoves (NPIC) (initiation 1983) for disseminating mud-based improved cookstoves to increase fuel use efficiency. There was emphasis on direct combustion and cogeneration by optimal utilization of country's biomass resources and deployment of biomass gasifiers for meeting unmet demand of electricity in villages.

In 1992, the Ministry of Non-Conventional Energy Resources was established for supporting the promotion of bioenergy programs. This ministry in now known as Ministry of New and Renewable Energy (MNRE). In the Tenth Five-Year Plan of India (2002–2007), Village Energy Security Programme (VESP) was launched with an objective to provide total energy requirement of villages including lighting, cooking and motive power with the involvement of local community.

There are several policies that are meant to promote electricity in entire country. These include Integrated Energy Policy 2005, National Electricity Policy 2005 and Rural Electrification Policy 2006. These policies support Decentralized Distributed Generation (DDG) facilities that offers scope for biomass-based energy and local distribution network. The National Policy on Biofuels 2009 promotes increased use of renewable energy as transport fuels (diesel and gasoline for vehicles) and suggested a target of 20% biofuels blending by 2017. However, there are difficulties in compulsory blending of 5% ethanol in petrol on account of many factors (EBTC 2012).

MNRE has initiated some of the major programs in the country for boosting bioenergy potential in the country through several schemes, viz. Biomass Power and Biomass Cogeneration in Sugar Mills (BPBCSM), Biogas Power Generation Programme (BPGP), Biomass Cogeneration Non-Bagasse (BCNB), Biomass Gasifier Programme (BGP), National Biogas and Manure Management Programme (NBMMP), Waste to Energy Programme (WEP), etc. This ministry has incentivized non-bagasse cogeneration in India since 2005. Non-bagasse includes by-products from all other industries, such as pulp and textiles. Besides fiscal incentives, some regulatory initiatives like renewable purchase standards (RPS) are there to promote bioenergy technologies.

A long-term techno-economic analysis using the MARKAL model shows that biomass-based electricity generation under an optimal greenhouse gas mitigation regime will penetrate to over 35,000 MW of electric power (9% of India's electricity generation) by the year 2035. A major issue in the long run shall be the availability of land. With improved biomass production and higher conversion efficiency, a smaller fraction of degraded land may support the market penetration during the next few decades. Although, the modern biomass program in India is in infancy, the environmental and other social benefits may provide opportunity for enhanced biomass penetration. However, low oil prices and continued environmental subsidies to fossil fuels may cause the opposite effect (Shukla 2014).

5 The Challenges

Well-diversified biomass resource is available in the country, but the challenge remains its collection, storage and transportation to processing plants economically. There are shortcomings in the entire value chain for biomass-based projects (logistics, chain management) that affect its adoptability. Besides the problem of seasonal fluctuations in biomass availability, most of the biomass sources are either burned or destroyed by the farmers or are used in non-productive alternative application options, which make resource access difficult consistently throughout the year (Joshi et al. 2016).

Although there has been success in the gasifier program, the matter of concern remains that many of the installed gasifiers are not in use. The primary reason for this failure is the distortion in capital cost of gasifier caused by the subsidy. The gasifier purchases were used as means to obtain a diesel pumpset at low cost (Ramana et al. 1997) since at current level of subsidy, the cost of a dual fuel mode gasifier (gasifier coupled with the diesel system) is less than the cost of the diesel set. Besides, the technological problems resulting in low utilization (less than 500 operational hours) persist due to multiple causes like the shortage of wood and substitution of wood for other uses. Technology R&D and reliable biomass supply are thus the key issues that still need to be sorted out.

One of the reasons that limit biomass-based energy penetration is the provision of subsidies to fossil fuels like kerosene. In commercial energy market, the biomass competes with kerosene in domestic use and with diesel in irrigation pumping and rural electricity generation. The key issue before the Indian policymakers is to develop the market for biomass energy services by ensuring reliable and enhanced biomass supply, removing the tariff distortions favouring fossil fuels and producing energy services reliably with modern biomass technologies at competitive cost.

Land is a critical resource for growing of plants in India. Therefore, whether it is energy plantation project or biofuel project, it has to be very carefully ensured; they are raised only on degraded soils or wastelands that are not suitable for agriculture so as to avoid a possible conflict of fuel versus food security.

6 The Future Strategies

Meeting the energy needs through bioenergy route has the advantage in addressing global concerns of containment of carbon emissions besides employment opportunities and rural development. However, most vital issue for biomass energy in India is the development of market for biomass energy services. The strategies need be directed towards ensuring reliable and enhanced biomass supply on one hand and offer cost-effective biomass energy services. Enhanced reliability of biomass supply shall need adequate logistics infrastructure in terms of logistics and distribution. Steps like modernization of biomass conversion technology and taking advantage of applications such as cogeneration in sugar mills and wood processing units will be useful in achieving economic production (Shaik and Kumar 2014).

Better management of biomass systems may be achieved by a shift in ownership (government to private, co-operative and community organizations), professional management of biomass plantations besides institutional and policy supports. There should be a mechanism for minimum support price for nonedible oilseeds that are used in production of biodiesel so as to provide a fair price to such growers. Oil Marketing Companies purchase bioethanol at minimum purchase price arrived based on the actual cost of production and import price of bioethanol. In the case of biodiesel, such a price should be linked to the prevailing retail diesel price. The transportation of biofuels across the country should be without any restriction. Financial incentives should be there for new and second-generation feedstocks, advanced technologies and conversion processes and production units based on new and second-generation feedstock.

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Some new areas for biofuel research and development may have promise like (i) Ethanol (gas and liquid fermentation from biomass and MSW), (ii) biodiesel (from algae grown on sunlight and carbon dioxide), (iii) hydrocarbon/s (including terpenes and methane by fermentation of biomass and MSW), and (iv) hydrogen (solar or fermentation of biomass and MSW; catalytic conversions of biomass and MSW). However, any sustainable technology must be able to produce fuel at competitive price and have low CAPEX and deployable at medium scale (~100–250 tonne/day), zero waste generation in the process and lower consumption of water. It is believed that support of scientific agencies in the country in promoting science for generating biofuel technologies and willingness on the part of industry to undertake risks will lead to develop, deploy and operate biofuel and bioenergy technologies in the next decade (Lali 2016).

7 Conclusion

The analysis of the resources and potential of biomass and other wastes in India suggests that there is considerable potential for conversion of such resources to energy. The technologies used for such conversion fall broadly in two categories, viz. thermochemical and biochemical. The industries and other agencies are practicing the conversion of various waste biomasses to energy to some extent. Bagasse cogeneration, using the waste in sugar mills, is a good example. Similarly several gasification-based cogeneration projects are successful for rural electrification. However, there is substantial gap in realization of the bioenergy potential. The government policies in encouraging bioenergy usage and in providing appropriate financial resources are considered extremely important in context of India. There are several options in promoting further use of the bioenergy and biofuels that reduces dependence on oil imports, leads to sustainable development, boosts economic growth and provide food security. Greater emphasis on policy initiatives for the exploration, extraction and use of bioenergy and biofuels in a way that does not adversely affect food production and adoption of new and improved technologies will be required in the future.

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Chapter 32
Pollinator Services in Coffee Agroforests of the Western Ghats

Smitha Krishnan, Kushalappa G. Cheppudira, and Jaboury Ghazoul

Abstract Pollination services have often been associated with distance to adjoining forest fragments, but few studies have evaluated this in the context of other factors such as fragment size, agroforest characteristics and management regime. We investigated the effects of size of the forest fragment, distance from the forest and the effect of management of the agroforest (shade, shade tree density, coffee plant characteristics and extent of coffee flowering following rain- mass flowering or irrigation-localized flowering) on bee visits, pollen tube abundance and seed-set within coffee agroforests in Kodagu, south India. Three social bees accounted for almost all pollination events. Pollen tube abundance and seed set were enhanced by pollinator visitation, but distance to forest fragments did not affect bee visitation or seed set. Size of the adjoining forest fragment positively affected bee visitation (only irrigated agroforests with localized flowering) and pollen tube abundance but had no effect on seed set. Irrigation, which stimulated flowering of individual agroforests asynchronously of others, resulted in a dramatic increase in pollinator visits, reflected by higher seed set. In rain-fed agroforests, high densities of bee-pollinated co-flowering shade trees reduced bee visits and pollen tube abundance, but high-density shade trees positively affected final seed set. The lack of distance and size effects of forest fragments on coffee seed set does not necessarily mean that forest fragments do not provide pollinator services but rather that such benefits are not explicit at the scale of the study. Wild bees depend upon forest remnants for nesting, and hence to benefit from their pollination services, the conservation of such forests becomes imperative. Further, other agroforest characteristics, notably irrigation, provide alternative means of enhancing pollination and seed production. Nevertheless, agroforest shade trees benefit coffee production, despite competing for pollinators, by ameliorating harsh climatic conditions during the long fruit mat-

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uration period and support pollinators within the landscape by providing forge to the bees during coffee non-flowering season. Farmers could enhance pollination services and improve crop production most effectively by managing the time of coffee flowering through irrigation such that agroforests flower nonsynchronously across the landscape.

Keywords Co-flowering trees · *Coffea canephora* · Coffee agroforests · Pollination success · Pollinators

1 Introduction

Heterogeneous landscape mosaics that include small forest patches have been suggested to be capable of supporting much biodiversity while also serving agricultural production through ecosystem service provision (Chazdon et al. 2009; Garcia et al. 2010). Such forest fragments can be important habitats for rare, endemic and endangered species (Bhagwat et al. 2005b). Additionally, forest patches in agricultural landscapes are thought to enhance crop productivity through pollination services at local scales for some crops (Klein et al. 2007), such as *Coffea arabica* (De Marco and Coelho 2004; Ricketts et al. 2004; Roubik 2002), *Coffea canephora* (Krishnan et al. 2012), *Solanum lycopersicum* (Greenleaf and Kremen 2006), *Macadamia integrifolia* and *Dimocarpus longan* (Blanche et al. 2006) and *Fragaria* × *ananassa* (Connelly et al. 2015). Loss of such seminatural habitats due to their transformation into crop lands thus reduces the ecosystem services that they otherwise benefited from (Diaz et al. 2006; Foley et al. 2005; Landis 2017; Millennium Ecosystem Assessment (MEA) 2005). It is therefore widely argued that the benefits of forests for crop production can incentivize farmers to retain and conserve such habitats (Jha and Vandermeer 2009; Klein et al. 2003b; Ricketts et al. 2004). In coffee-producing landscapes, pollination success is, however, also shaped by many factors related to tree cover, both within coffee agroforests and across the landscape. The extent of coffee flowering (Jha and Vandermeer 2009; Klein et al. 2003b), the abundance of flowering herbs (Klein et al. 2003b), shade cover (Jha and Vandermeer 2009; Klein et al. 2002; Lin 2009; Vergara and Badano 2009), relative humidity (Klein et al. 2002) and shade tree density (Klein et al. 2002, 2003a) all have a role in determining pollination visitation or final fruit/seed set.

The coffee agroforests of Kodagu have a particularly high density and diversity of shade trees (Bhagwat et al. 2005b; Krishnan et al. 2012), although there is a trend towards simplification of these systems through the partial or complete replacement of native shade trees with exotic *Grevillea robusta*. In seeking to justify the retention of native shade trees through pollinator service arguments, we must evaluate both the benefits, which are well documented, and the disadvantages of native shade trees for pollinator services. We recognize the many benefits that native shade trees provide to agroforestry systems, but here we also consider possible disadvantages of retaining native trees in the landscape. One of these is that such trees might compete with coffee for the attention of limited numbers of pollinators. If many shade tree species flower synchronously with coffee, it is possible that pollinators are preferentially attracted to these tree floral resources and away from coffee flowers, with consequent impacts for coffee productivity. We therefore investigate how pollinator abundance, pollen tube abundance and fruit production of coffee in South India are affected by forest and tree abundance in the landscape, as well as features of the coffee agroforests. Specifically, we explore three principal questions:

1. Do insects enhance coffee fruit and seed set and, if so, to what extent?
2. Do management interventions and agroforest characteristics, notably irrigation and shade trees (as alternative floral resource providers), affect pollinator abundance, pollination success and seed set?
3. Does size of forest fragments affect abundance of pollinators and pollination success in adjacent coffee agroforests and subsequent seed set?

2 Methods

2.1 Study Region

Kodagu district is in the southern part of India along the Western Ghats biodiversity hotspot in the state of Karnataka. About 32.5% of the geographical area (4106 km^2) of Kodagu is covered by coffee agroforests (majority being *Coffea canephora*), 46% by forests and 21.5% by paddy fields, water bodies and human settlements. Kodagu has a high density of sacred forests (1214 sacred forests, equivalent to 2% of the land area), which though owned by the government, are mainly maintained and protected by the community due to cultural and spiritual associations (Garcia et al. 2010; Ramakrishnan et al. 2000). Additionally, there exist many privately owned forests, many of which are not well documented. On average, every 3 km^2 of the land area has one or more sacred groves and/or private forests (Bhagwat et al. 2005a). About 46% of these forests are smaller than 0.4 hectare (Tambat et al. 2005), and 80% are less than 2 hectares (Bhagwat 2002; Ramakrishnan et al. 2000), with very few large forest patches (up to 500 ha). Despite these forests being protected by law, they are rapidly disappearing due to encroachment by coffee farmers (Ormsby and Bhagwat 2010). Sacred groves retain relatively high biodiversity, comparable to protected forests (Bhagwat et al. 2005b), and provide important nesting sites for bees (Krishnan 2011). Biodiversity on private forests, though undocumented, is expected to be similar to sacred forests. Privately owned forests are, however, much more prone to conversion to coffee agroforests (Garcia and Pascal 2006; Garcia et al. 2010).

Most coffee agroforests in Kodagu are established under native forest cover by clearing the understorey. The shade trees help to maintain a relatively constant relative humidity through the year and provide protective shade which is especially important during the 3–5-month dry season. In recent years, coffee production on some agroforests has been ‘intensified’ as farmers adopt irrigation to initiate flowering, which otherwise occurs 8 days after the first rains at the end of the dry season (Ramakrishnan et al. 2000). The shade tree canopy is also being opened up to provide more light to the coffee crop or is being replaced with fast-growing exotics such as *Grevillea robusta* that provide diffused shade (Garcia et al. 2010).

2.2 Selection of Study Locations

Our study was conducted in Virajpet Taluk (12°00′–12°29′N and 75°39′–76°33′E) located in Kodagu district. We selected coffee (*Coffea canephora* hence forth referred to as ‘coffee’) agroforests adjoining 41 forest fragments (in 41 different locations), of which 34 ranged in sizes from 0.3 ha to 20 ha (sacred forests) and additional agroforests adjoining seven protected forests of sizes ≥200 ha. The size of the small forest fragments was obtained by mapping them using a GPS (Garmin 60CSx), while that of the large forests was obtained from government records. The forests were selected such that the distance to the next nearest forest was at least 1000 m. All studies were conducted during 2007–2009.

2.3 Floral Visitors

Pollinator observations and fruit-set assessments within coffee agroforests adjoining each of the 41 forest fragments were undertaken at distances of <10, 50, 100, 250 and 500 m from the forest edge allowing us to sample a wide sampling of pollinators both near and far from the forest fragment. We had a total of 205 sites of which 47 sites were discarded from our final analysis due to rain on the day of flowering or missing information. Three to five coffee plants were selected at each site such that they were separated from each other by at least 10 m. On the selected plants, five branches were selected at random and marked with a tie wrap at either end of the branch such that six clusters (flowers at the axils of two opposite leaves or at each node) were enclosed between them. Clusters at the tip of the branch were not considered for the study since we observed that such clusters were often damaged during fruit setting or produced fewer fruits than the subsequent clusters. The buds on the six marked clusters were counted 2 days prior to flowering. Pollinator observations were made during simultaneous 15-minute observation periods of the five selected branches at each plant and the abundance of flower visitors was recorded species wise. Species that were not identified on field were collected for later identification after the observation time whenever possible. The number of flowers visited by the bees was also recorded simultaneously. In the event of a high abundance of pollinators, only three branches were observed initially, and the remaining two were observed immediately after for the same duration (15 min). This observation duration was based on an earlier pilot study (using 30 replicated test runs for 30 min of observation and 51 test runs of 20 min of pollinator observation periods) which determined that 15 min provided a representative measure of pollinator abundance and diversity. This length of observation is also comparable with that adopted by other similar studies (Jha and Vandermeer 2009; Ricketts 2004; Veddeler et al. 2006).

Observation time was additionally constrained by the need to replicate observations over many sites. We randomized the order in which the data was collected from the various distances. Relative humidity and temperature were recorded at the time of pollinator observations. Data collected on days which experienced rainfall were discarded from the analysis as rainfall on the day of flowering negatively and substantially affects fruit-set independent of pollinator activity (DaMatta et al. 2007). All pollinator observations were carried out between February and April (according to the period of coffee flowering in the 3 years 2007, 2008 and 2009).

2.4 Pollination Experiments

Pollination experiments were conducted in a subset (28 of the 41) of the locations accounting to 140 agroforests to evaluate the contribution of wind to coffee fruit set. Due to rain on the day of observation, data from 28 agroforests had to be discarded. The five branches marked on each of the five plants used for floral visitor observation studies were also used for open-pollination experiments which gave us the contribution of wind + insect pollination. One branch (with six marked clusters) on each of the same marked plants that were used for the open-pollination studies was used for wind-pollination treatments where pollinators were excluded by covering the branch with a mesh bag with mesh size of 0.8–1.2 mm before anthesis. The bags were left on the branch till the flowers had begun to wilt and were unattractive to bees (for 3 days). The treatments were applied on the same plant replicates to eliminate the influence of other possible variables (Krishnan et al. 2012). The final fruit set was recorded just prior to the harvest of the ripe fruits. The difference between the open-pollinated and wind-pollinated branches gave us the contribution of bees towards coffee pollination.

2.5 Pollen Tube Abundance

To determine pollen tube abundance (PTA – the number of fully developed pollen tubes that reach the base of the ovary in each flower), we enumerated pollen tubes within styles of coffee flowers at all the 205 sites on which the floral visitors and fruit production were evaluated. Before doing so, we first determined the appropriate time of collection following anthesis to allow for pollen tube to reach the ovary which was determined as 26–49 h (Krishnan 2011). Therefore, flower samples were collected 72 h after flowering to ensure that sufficient time had elapsed for detection of pollen tubes along the style.

Twenty randomly selected flowers per plant were collected from all study sites from ten random open-pollinated plants from all the 205 sites where the pollinator observations were conducted. The styles were stored in FAA fixative (formalin/acetic acid/70% ethanol in 5:5:90 proportions, respectively) (Dumas and Knox 1983). In the laboratory, the styles were washed thoroughly in water and softened in 8 N sodium hydroxide for 18 h. The softened tissue was rinsed in water several times before being stained in decolorized aniline blue solution (0.1% solution of water soluble aniline blue dye in 0.1 *M* K_3PO_4) for 18 h (Martin 1959) in darkened containers. Five styles per plant were randomly selected totalling to 50 styles observed per site (total 205 sites). The styles were crushed under a glass slide carefully and were observed using an epifluorescence microscope under ultraviolet light at 360 nm at 100x magnification. Pollen tubes fluoresce (green to bluish-green fluorescence) under ultraviolet light and were easily enumerated (Lashermes et al. 1996). A total of 10,250 styles were observed for the study. The number of pollinated styles (with pollen that germinated) and the number of pollen tubes per style (actual count of pollen tubes that reach the base of the style) were recorded for each of the 205 sites. Of the total 205 study sites, only 160 were used for the analysis either due to rain on the day of flowering or missing information.

2.6 Seed-set

The ripened mature fruits (Fig. 32.1) on the same marked branches on which pollinators were observed were counted and collected around 10 months after flowering. Total seeds were calculated by counting the number of fully developed seeds. The fruits were segregated as cherries (two seeded) and peaberries (single seeded), and

Fig. 32.1 Ripe *Coffea canephora* fruits, ready for harvest

the number of seeds was added up to obtain the final count of seeds. The proportion of ovules (two per flower) that developed into seeds was calculated and henceforth is referred to as seed-set.

2.7 Agroforest Characteristics

Canopy cover (as percentage) above each of the marked coffee bushes was recorded using a densiometer (Lemmon 1956). The crown diameter of the marked coffee bushes was also measured. An area of 3000 m^2 was sampled at each location to obtain the species of the shade trees and their density in the agroforests. The flowering time of shade tree species was obtained from various publications, databases and secondary sources and was used to estimate the number of bee-pollinated trees in flower during coffee flowering. Although *Grevillea robusta* is visited by bees, it is not included under bee-pollinated shade trees in our analysis due to its inconsistency in flowering and flowering times in Kodagu as is the case in its non-native range.

2.8 Management Scenarios

Irrigation induces flowering in coffee, as do the first summer showers. While irrigation induces flowering at the agroforest scale (i.e. the scale at which irrigation is applied most often <3 ha in area), the first summer showers (referred to as blossom showers) induce flowering over a much larger region commensurate with the area inundated by such showers (encompassing hundreds of hectares). This leads to two contrasting flowering scenarios, which were recorded for the study: irrigation leading to isolated flowering patches at agroforest scale and rain to mass flowering at the landscape scale. The management used to initiate flowering (rain and irrigation) was used as a categorical variable.

2.9 Statistical Analyses

Three to five coffee plants each were observed at five distance classes over 41 locations leading to 205 sites (158 usable sites). We used generalized linear models (GLM) for all analyses. We analysed the total and species-wise (three main species groups, *Apis dorsata*, *A. cerana indica* and *Tetragonula iridipennis*) pollinator abundance at coffee flowers with respect to management practice (a categorical variable with two levels, irrigation/rain), size of the nearest forest patch (hectares, log transformed), relative humidity (%) during observations, canopy cover (%) and density of co-flowering bee-pollinated trees (ha^{-1}). We used a negative binomial GLM since the response variable was overdispersed count data.

The effect of pollinator abundance (all pollinators/*Apis dorsata*/*A. cerana indica*/*Tetragonula iridipennis*) at coffee flowers, size of the nearest forest (log transformed), crown width of coffee bush (crown width was correlated with stem girth and height), density of bee-pollinated trees that flowered during the observation periods and/or density of shade trees, canopy cover and management practice (two levels – irrigation and rain as a categorical variable) on the response pollen tube abundance and seed set were evaluated. The abundance of pollinators was highly correlated with total floral visits (Spearman's correlation coefficient = 0.98, $p \leq 0.001$), and hence we interpret pollinator abundance as an appropriate proxy for all floral visits. A binomial GLM was used in the model with fruit production and pollen tube abundance as the response since they were proportions. Arithmetic means ± standard deviations of the measure variables are provided when relevant.

The results of the most parsimonious model have been discussed in this paper. The final model was checked for heteroscedasticity. The independent variables in the models with interactions were centred to reduce multicollinearity (Quinn and Keough 2004). To compare the treatment effects (open- and wind-pollinated flowers) of the pollination study on seed output, a Wilcoxon paired test was used. The non-parametric test was used since the data deviated from normality. The statistical software 'R' version 3.3.1 (R Development Core Team 2016) was used for all the statistical analyses.

3 Results

3.1 Coffee Pollinators and Seed Output

About 95.7% of all the coffee visitors were bees. Social bees (*Apis dorsata*, *A. cerana indica*, *A. florea* and *Tetragonula iridipennis*) accounted for 94.6% of all floral visitors. The remaining visitors were solitary bees (1.1%), dipterans (0.8%) and others (3.5%). About 33 ± 11% of the open-pollinated flowers developed into fruits of which 66 ± 13% developed into two-seeded cherries and 34 ± 13% into one-seeded peaberries. Seed output in open-pollinated flowers accounted to 27 ± 10%. Fruit production by wind-pollination (excluding insects) was significantly lower than open-pollination treatments and accounted to only 22 ± 12% ($W = 5107$, p-value ≤ 0.001). The proportion of wind-pollinated fruits that developed as cherries and the final seed output was 51 ± 15% and 16 ± 9% ($W = 5234.5$, p-value ≤ 0.001), respectively, which was significantly lower than that of open-pollinated flowers (Krishnan et al. 2012).

Since social bees comprised the large majority of flower visitors, we focused on these species. The effect of *Apis florea* on coffee seed set was not analysed since it was only an occasional visitor (0.6% of all social bee visits). Across all sites, *Apis dorsata* (Fig. 32.2) was the most frequent floral visitor (58% of all social bees

Fig. 32.2 *Apis dorsata* foraging on *Coffea canephora* flowers

Fig. 32.3 *Apis cerana indica* foraging on *Coffea canephora* flowers

visiting flowers), followed by *Apis cerana indica* (Fig. 32.3, 23.4%) and *Tetragonula iridipennis* (Fig. 32.4, 18%). The extent of coffee flowering within the landscape had an influence on the pollinator abundance (Fig. 32.5, Table 32.1). Pollen tube abundance increased with an increase in pollinator abundance and specifically in case of an increase in abundance of *Apis dorsata* and *Tetragonula iridipennis* (Tables 32.5 and 32.6). There was also a similar increase in seed set with an increase

Fig. 32.4 A colony of *Tetragonula iridipennis* nesting in a wall

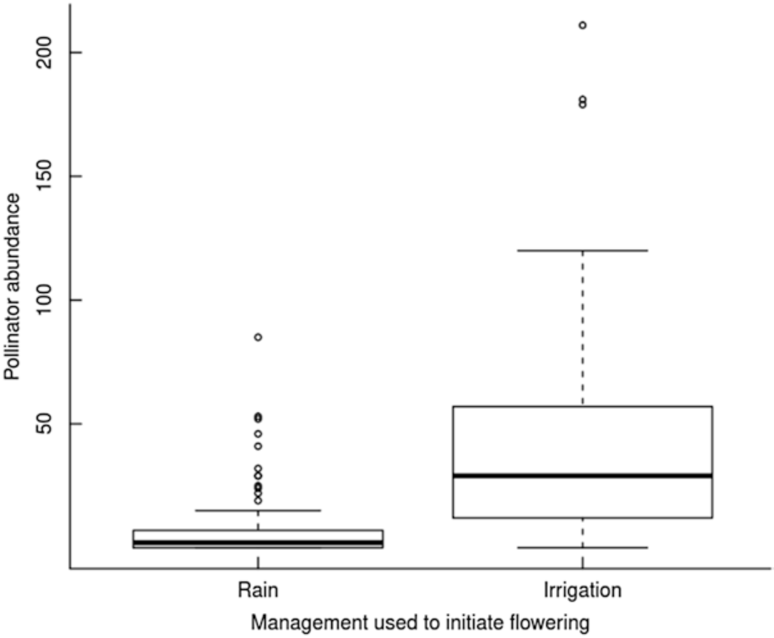

Fig. 32.5 Pollinator abundance in two management scenarios: mass flowering initiated by rain and staggered flowering initiated by irrigation. Median and interquartile ranges represented by bold line and box, whiskers represent 1.5 times the interquartile range, and outliers are shown outside this range. $F = 57.5$, $p \leq 0.001$

Table 32.1 Effects of agroforest and landscape variables on pollinator abundance at coffee flowers (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: pollinator abundance	Estimate	Std. error	*z*-value	*p*-value
Intercept	1.807	0.1588	11.38	≤ 0.001
Management (irrigation)	1.925	0.2140	8.99	≤ 0.001
Alternative resources (trees ha^{-1})	−0.010	0.0032	−3.13	0.002
Forest size in hectares (log)	−0.032	0.0847	−0.37	0.709
Relative air humidity (%)	−0.054	0.0151	−3.59	≤ 0.001
Alternative resources: management (I)	0.008	0.0041	1.94	0.052
Forest size (log): management (I)	0.296	0.1107	2.67	0.008
Relative air humidity: management (I)	0.046	0.0191	2.42	0.015

Variables dropped from the model with stepwise elimination: Number of flowers, distance from forest, shade cover, distance from forest: Size of the adjoining forest management: Number of flowers, management: distance from forest, management: shade cover, management: relative humidity

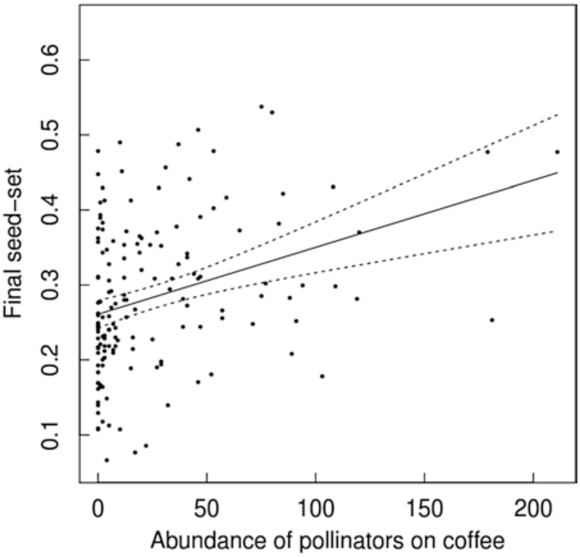

Fig. 32.6 Effect of pollinator abundance (individuals observed on three coffee plants on five selected branches each for 15 min) on seed output. Seed output or seed set is the proportion of ovules that developed as seeds. Full line represents the fitted pollinator abundance-seed output relationship and dotted lines represent the 95% confidence intervals. $t = 2.74$, $p \leq 0.007$

in pollinator abundance (Fig. 32.6) and particularly so in the case of *A. dorsata* (Table 32.8). There was an interactive effect of *A. dorsata* and the type of management used to initiate flowering in coffee on seed set. The increase in seed set was steeper in the case of rain-fed sites compared to irrigated with an increase in *A. dorsata* abundance, while *A. cerana indica* and *Tetragonula iridipennis* abundance had no apparent influence on seed set.

3.2 *Influence of Contrasting Flowering Scenarios*

Flowering in coffee is initiated either by rain or irrigation (after 8 days) after a dry spell of about 3 months. The two modes of initiation of flowering create very contrasting flowering scenarios. Irrigation leads to flowering at a small agroforest scale which is often a continuous patch of less than 3 ha in size, while flowering following rain is often at a much grander scale of over >1000 ha in size. The overall pollinator visitation at coffee flowers was positively affected by irrigation and was significantly higher than rain-fed sites (Fig. 32.5), and this effect was also observed among individual bee species (Tables 32.2, 32.3 and 32.4). Seed set was also significantly greater in irrigated than rain-fed sites (Fig. 32.7). Specifically, contrasting flowering scenarios led to very varied effects of the remaining explanatory variables on the responses which are explained in detail below.

Table 32.2 Effects of agroforest and landscape variables on *Apis dorsata* abundance at coffee flowers (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: abundance of *Apis dorsata*	Estimate	Std. error	*z*-value	*p*-value
Intercept	0.932	0.2573	3.62	≤0.001
Management (irrigation)	2.225	0.3428	6.49	≤0.001
Alternative resources (trees ha^{-1})	−0.025	0.0051	−4.841	≤0.001
Forest size in hectares (log)	−0.467	0.2855	−1.63	0.102
Alternative resources: management (I)	0.020	0.0065	3.13	0.002
Forest size (log): management (I)	1.523	0.3838	3.969	≤0.001

Variables dropped from the model with stepwise elimination: Number of flowers, distance from forest, shade cover, distance from forest: size of the adjoining forest, management: Number of flowers, management: distance from forest, management: shade cover, management: relative humidity

Table 32.3 Effects of agroforest and landscape variables on *Apis cerana indica* abundance at coffee flowers (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: *Apis cerana indica*	Estimate	Std. error	*z*-value	*p*-value
Intercept	0.433	0.1988	2.18	0.029
Management (irrigation)	1.503	0.2625	5.73	≤0.001
Relative air humidity (%)	−0.057	0.0190	−2.98	0.003
Relative air humidity: management (I)	0.098	0.0237	4.14	≤0.001

Variables dropped from the model with stepwise elimination: Alternative resources, Number of flowers, distance from forest, size of the adjoining forest, shade cover, relative humidity, distance from forest: size of the adjoining forest, management: Number of flowers, management: alternative resources, management: distance from forest, management: size of the adjoining forest, management: shade cover

Table 32.4 Effects of agroforest and landscape variables on *Tetragonula iridipennis* abundance at coffee flowers (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: *Tetragonula iridipennis*	Estimate	Std. error	*z*-value	*p*-value
Intercept	−0.394	0.2633	−1.50	0.134
Management (irrigation)	2.151	0.3186	6.75	≤0.001
Number of flowers	−0.012	0.0059	−2.43	0.015
Relative air humidity (%)	−0.061	0.0118	−5.16	≤0.001
Number of flowers: management (I)	0.035	0.0111	3.15	0.002

Variables dropped from the model with stepwise elimination: Alternative resources, distance from forest, size of the adjoining forest, shade cover, distance from forest: size of the adjoining forest, management: Number of flowers, management: alternative resources, management: distance from forest, management: size of the adjoining forest, management: shade cover, management: relative humidity

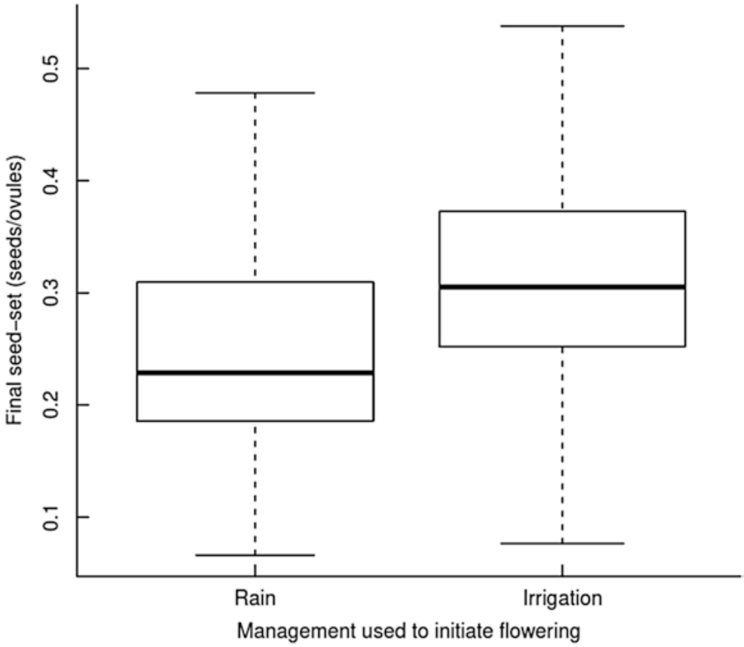

Fig. 32.7 Final seed set (proportion of ovules that developed into seeds) under two management scenarios used to initiate flowering. Rain-fed sites mass flowered at a landscape scale, while irrigated sites flowered at agroforest scale. Median and interquartile ranges are represented by bold line and box, whiskers represent 1.5 times the interquartile range, and outliers are shown outside this range. $F = 17.41$, $p \leq 0.001$

Table 32.5 Effects of pollinators, agroforest and landscape variables on coffee pollen tube abundance (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: pollen tube abundance	Estimate	Std. error	*z*-value	*p*-value
Intercept	1.641	0.0738	22.24	≤0.001
Management (irrigation)	0.212	0.1149	1.85	0.067
Pollinator abundance	0.007	0.0016	4.48	≤0.001
Coffee bush crown width	0.005	0.0018	3.11	0.002
Forest size in hectares (log)	0.179	0.0593	3.02	0.003
Alternative resources (trees ha^{-1})	−0.000	0.0014	−0.06	0.951
Alternative resources: management (I)	0.005	0.0019	2.36	0.020

Variables dropped from the model with stepwise elimination: shade cover, relative humidity, distance from forest: size of the adjoining forest, management: pollinator abundance, management: coffee bush crown width, management: distance from forest, management: shade cover, management: relative humidity

3.3 *Effect of Distance from and Size of Adjoining Forest*

Pollinator visitation (particularly by *A. dorsata*) in irrigated agroforests and pollen tube abundance increased with an increase in size of the adjoining forest fragment (Tables 32.1, 32.2 and 32.5). Distance from forest did not have a significant effect on any of our response variables.

3.4 *Influence of Shade Trees*

Coffee agroforests had high shade tree densities (297 ± 90 ha^{-1}, range 120–543 ha^{-1}) of which a large number (165 ± 55 ha^{-1}) were bee pollinated, and the flowering times of 112 ± 54 ha^{-1} of these trees overlaps with coffee. There was a significant decline in visits by pollinators, particularly *A. dorsata* with increasing density of co-flowering trees in rain-fed agroforests (Tables 32.1 and 32.2). A reduction in pollen tube abundance with an increase in alterative floral resources was also observed in rain-fed agroforests (Table 32.5). Although tree density and number of trees providing alternative floral resources were highly correlated, alternative floral resources did not have a significant influence on coffee seed set but tree density had. Coffee seed set increased with an increase in density of shade trees only in rain-fed agroforests (Tables 32.6 and 32.7).

Table 32.6 Effects of bees (species wise), agroforest and landscape variables on coffee pollen tube abundance (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: pollen tube abundance	Estimate	Std. error	z-value	p-value
Intercept	1.654	0.0756	21.89	≤0.001
Management (irrigation)	0.186	0.1184	1.58	0.117
Apis dorsata abundance	0.007	0.0021	3.31	0.001
Tetragonula iridipennis abundance	0.018	0.0068	2.60	0.010
Coffee bush crown width	0.006	0.0019	3.17	0.002
Forest size in hectares	0.171	0.0605	2.83	0.005
Alternative resources (trees ha^{-1})	−0.000	0.0014	−0.09	0.930
Alternative resources: management (I)	0.004	0.002	2.27	0.024

Variables dropped from the model with stepwise elimination: *Apis cerana indica* abundance, shade cover, relative humidity, *Apis dorsata* abundance: management, *Tetragonula iridipennis*: Management, distance from forest: size of the adjoining forest, management: coffee bush crown width, management: size of the adjoining forest, management: shade cover, management: relative humidity

Table 32.7 Effects of pollinators, agroforest and landscape variables on coffee seed set (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: seed set	Estimate	Std. error	z-value	p-value
Intercept	−1.037	0.0620	−16.72	≤0.001
Management (irrigation)	0.233	0.0872	2.68	0.008
Pollinator abundance	0.003	0.0011	2.47	0.014
Tree density (trees ha^{-1})	0.002	0.0008	2.23	0.027
Tree density: management (I)	−0.002	0.0009	2.33	0.021

Variables dropped from the model with stepwise elimination: coffee bush crown width, distance from forest, size of the adjoining forest, shade cover, relative humidity, pollinator abundance: management, distance from forest: size of the adjoining forest, management: coffee bush crown width, management: distance from forest, management: size of the adjoining forest, management: shade cover, management: relative humidity

3.5 Variables of Lesser Importance

Relative humidity was negatively associated with bee visitation in rain-fed sites only, though with different responses from the individual pollinator groups (Tables 32.2, 32.3 and 32.4). Abundance of *Tetragonula iridipennis* reduced with an increase in relative humidity, but abundance of *Apis cerana indica* reduced only in rain-fed agroforests and increased in irrigated agroforests with an increase in relative humidity. *Apis dorsata* did not seem to be influenced. Finally, pollen tube abundance increased with coffee crown width in both rain-fed and irrigated sites though no

Table 32.8 Effects of bees (species wise), agroforest and landscape variables on coffee seed set (only significant results have been displayed, in addition to the main effects when the variables were significant in interactions)

Response: seed set	Estimate	Std. error	z-value	p-value
Intercept	−0.936	0.0728	−12.85	≤0.001
Management (irrigation)	0.144	0.0885	1.63	0.106
Apis dorsata abundance	0.014	0.004	3.24	0.002
Tree density (trees ha^{-1})	0.002	0.0008	2.79	0.006
Apis dorsata abundance: management (I)	−0.010	0.0045	2.31	0.022
Tree density: management (I)	−0.003	0.0009	2.94	0.004

Variables dropped from the model with stepwise elimination: *Tetragonula iridipennis* abundance, distance from forest, size of the adjoining forest, coffee bush crown width, shade cover, relative humidity, abundance: management, *Tetragonula iridipennis*: Management, distance from forest: size of the adjoining forest, management: coffee bush crown width, management: distance from forest

effect on pollinator visitation or seed set was detected. Shade cover and number of flowers on the observed branch did not have a significant influence on any of the response variables (Table 32.8).

4 Discussion

The importance of variables other than distance to the forest as variables that affect bee visitation, pollen tube abundance and seed set is established in this study. Contrary to a few previous studies (Klein et al. 2003b; Ricketts et al. 2004), distance to the nearest forest fragment in Kodagu did not affect either bee visitation or seed set. Bee visitation, pollen tube abundance and coffee seed set were particularly influenced by irrigation and the abundance of alternative floral resources on shade trees within coffee agroforests. The effects of forest size on pollination services appear to be mediated by irrigation or rain (extent of the crop in flower). Our results therefore indicate that pollination services cannot be easily attributed solely to the abundance and distribution of forest fragments within the landscape.

4.1 Extent of Flowering

This study looked at flowering at much larger scales (agroforest scale = irrigated, landscape scale = rain-fed) which was created by the management methods used to initiate flowering. Irrigation is used by farmers to initiate flowering independently of rainfall (which is the natural trigger). Farmers using irrigation for this purpose can also initiate flowering within their agroforests independently of other agroforests in the landscape (Boreux et al. 2013) and by so doing attract a disproportionate number of pollinators, while mass-flowering coffee agroforests received very few pollinator visits due to dispersion of pollinators across large expanses of coffee in flower (Krishnan et al. 2012). Studies even at smaller scales (5, 10, 100 m scale and at field, shrub and branch scale) consistently show similar responses (Jha and Vandermeer 2009; Veddeler et al. 2006). Benefits of higher visits by bees in irrigated agroforests (flowering at agroforest scale) are reflected in improved pollen tube abundance, a benefit that persists through to seed set in irrigated agroforests.

4.2 Importance of Pollinators

Open-pollinated flowers received higher amounts of pollen grains (231 ± 135) as compared to wind-pollinated (106 ± 45) flowers. The importance of insects in augmenting pollination success, fruit set and seed output is evident when open-pollinated and wind-pollinated experiments are compared. The lower proportion of peaberries in open-pollination treatments further emphasizes the importance of pollinators in coffee production.

Bees are therefore important in augmenting the productivity of coffee and in improving the quality of the fruit (more cherries than peaberries). In Kodagu, social bees are overwhelmingly important as pollinators, and around 95% of visits to coffee flowers are due to a few social bees and 58% by *Apis dorsata* alone.

4.3 Effect of Alternative Floral Resources

The presence of co-flowering trees depresses visitation of pollinators to coffee, especially in mass-flowering agroforests. This effect is not due to shade, which had no significant effect on pollinators at coffee. Instead, it is likely that alternative floral resources provided by co-flowering shade trees attract pollinators, especially *Apis dorsata* (Table 32.2), away from coffee. In our study sites, considerable bee activity on *Syzygium cumini*, a common profusely co-flowering shade tree in agroforests, often contrasted with hardly any visits to coffee in the same agroforests. Each *S. cumini* flower contains twice (or more) as much nectar as coffee (7.2 ± 1.52 μl vs. 3.5 ± 2 μl) and a higher sugar concentration (26.3% ± 9.3 vs. 21% ± 4, respectively). On a per flower basis, *S. cumini* is therefore more rewarding than coffee. It is also a profusely flowering species, making it attractive to pollinators (see Box 32.1).

Box 32.1: Methods

Coffee Nectar Quantity and Quality

Ten plants were selected, and one branch per plant was covered with a mesh bag one day before the day of flowering to exclude pollinators. On the day of anthesis, floral nectar volume and sugar content were measured hourly from 10:00 am to 3:00 pm, reflecting the period in which the bees are most active (*pers. obs.*). At least ten flowers were sampled at each hourly interval. Nectar volume was determined using 5 μl glass micropipettes, and sugar concentrations (as a percentage) were measured using a pocket refractometer (Bellingham & Stanley Ltd.) (Dafni 1992). Mesh bags were replaced after each measurement. Nectar volume and sugar concentration in *Syzygium cumini* were measured in open flowers since it was an unplanned experiment.

Results

Flowers of *Coffea canephora* produced <1 μl to 8.5 μl (mean ± SD = 3.5 ± 2 μl) of nectar with a sugar content of 21% (±4). Each cluster of flowers at the nodes consisted of 40 (±14) flowers hence representing an abundant resource for bees.

Open flowers of *Syzygium cumini* produced 7.2 ± 1.52 μl of nectar with the sugar concentration amounting to 26.3% ± 9.3. *Syzygium cumini* is also a species that flowers profusely, but was not quantified for this study.

Reference

Dafni A (1992) Pollination ecology: A practical approach. Oxford University Press, Oxford

Coffee nectar contains caffeine that apparently increases the foraging frequency, persistency and specificity to the forage location of honey bees, but these studies were conducted using feeders in artificial conditions (Couvillon et al. 2015; Wright et al. 2013). The results show that bees do respond to alternate floral resources in a mass-flowering coffee landscape to an extent that could depress pollinator visitation to coffee.

Despite a negative influence of alternative floral resources on pollinator abundance and pollination success, there was no impact on seed set (results not shown). Agroforests with a high density of alternative floral resources also harboured a high tree density. An increase in shade tree density had a significant positive effect on seed set only in rain-fed sites though the density of trees co-flowering with coffee did not have a significant effect. Agroforests that are rain-fed often experience drought stress, especially when monsoonal rains are delayed, and coffee plants in well-shaded agroforests are better able to withstand longer periods of dry conditions as shade trees ameliorate the microclimate. Additionally, coffee needs rainfall (or irrigation) 2 weeks after flowering for improved fruit retention, but this is less critical in well-shaded agroforests which have better fruit retention (Lin 2009) since such agroforests benefit from leaf litter which helps in retaining the soil moisture for longer periods. Thus, while shade trees might reduce pollinator abundance and pollen tube abundance, they may nevertheless enhance fruit production by improving fruit retention. Hence retention of shade trees, especially in rain-fed agroforests, is overall likely to enhance coffee production. Informed management therefore should take account of these contrasting effects.

4.4 Distance and Forest Size

Negative effect of distance to forest patches on pollinator services has been observed in many studies (Garibaldi et al. 2011; Ricketts et al. 2008) though other studies have shown little effect (see Chacoff et al. 2008; Winfree et al. 2008) or species-specific responses (Greenleaf and Kremen 2006) to forest proximity. The lack of an obvious effect of distance to forest on pollination success in this study is likely due to different reasons for the different pollinators. Nesting and foraging resources for both *Apis cerana indica* and *Tetragonula iridipennis* are available within or around agroforests and are thus independent of forest habitat availability.

Apis dorsata, on the other hand, is dependent upon forest fragments and especially large trees for it nesting requirements, but its large foraging range (>500 m), coupled with the abundance of small forest fragments within the landscape (a forest fragment for every 3 km^2, Bhagwat et al. 2005a), means that the large majority of agroforests are sufficiently close to *A. dorsata* nests to secure the necessary pollination services. Although the size of the forest significantly increases the number of successfully developed pollen tubes, this effect did not translate into an increase in final seed set.

Apis dorsata has a foraging range that extends over several kilometres and is reported to be up to 21.8 km (but mostly travels within 1 to 4 km from its nest) (Dyer and Seeley 1994). *Apis cerana indica* is known to forage up to 2 km from the nest (Dyer and Seeley 1991), while foraging distances of *Tetragonula iridipennis* are likely to be limited to less than 1 km (Wille 1983). Although forest patches within Kodagu are generally small, their density within the landscape ensures that most coffee agroforests are located within 1 or 2 kilometres of a forest patch, distances that are well within the foraging range of *Apis* species.

Coffee agroforests in Kodagu are often shaded by a variety of native trees that also provide floral resources within the matrix and often throughout the year. Consequently, the benefits provided specifically by forest fragments through the provision of pollinator services cannot be easily separated from the provision of pollinator services by the broader landscape matrix within which the forest fragments lie. Indeed, native trees in coffee agroforests might not only facilitate the movement of bees across the landscape between forest fragments but might also provide nesting and foraging resources independently of forest fragments.

Apis dorsata does, however, appear to be largely dependent on natural forest patches for nesting (occasional nests were found on trees within agroforests, but most shade trees are pruned, and the availability of suitable nesting branches is often limited). In Kodagu, the recent loss of forest fragments is of concern for the persistence of *Apis dorsata*. During the 3 years of this study, 1 (2.1 ha) of the 34 smaller forest fragments that we included in our study was cleared, resulting in the loss of 17 *Apis dorsata* colonies (SK unpublished data), but whether this locally undermines coffee production to impact farmer profits has yet to be determined. A study from the same region shows that the number of *A. dorsata* colonies increased with an increase in size of the forest fragment ($t = 5.57$, $p \leq 0.001$). We attribute the positive effect of fragment size on coffee pollination in Kodagu to the increased abundance of *A. dorsata* specifically (Table 32.2) corresponding to a generally higher number of *A. dorsata* colonies in larger fragments (Krishnan 2011). Nevertheless, seed set was not affected by distance to, or size of forest fragments, at least at the scales of assessment within this study, and hence applying pollinator service arguments to the conservation of native forest patches is difficult to justify to individual farmers.

4.5 Management Implications and Scenarios

The pollinator service benefit provided by forest patches is subject to the pattern of coffee flowering across the landscape. Extensive and synchronous flowering following widespread rainfall leads to the dilution of pollinator services as pollinators forage over a wider area (as also demonstrated by Boreux et al. 2016, Jha and Vandermeer 2009 and Veddeler et al. 2006). Proximity to a forest patch, even a large one, in such situations provides no clear advantage to the farmer. Irrigation allows farmers to induce coffee flowering at a time when few other agroforests are flowering and so benefits by enhanced pollination by attracting a disproportionate number of pollinators to a limited flowering area. Thus, the conservation of local forest patches close to coffee agroforests is likely to most benefit farmers when they also adopt irrigation. Management practices in the Kodagu landscape could therefore include the promotion of irrigation coupled with a coordinated schedule that minimizes the simultaneous flowering of agroforests.

Improving pollination visitation and coffee production through irrigation alone might appear to undermine pollinator service arguments for conserving forests, but it should be noted that the presence of neighbouring forests, and particularly large forest patches, further improves pollination of irrigated crops (Tables 32.1, 32.2 and 32.5). In other words, a farmer can substantially improve pollinator visitation and crop production through irrigation, but marginal benefits to pollination are increased further with increasing size of neighbouring forest patches. Although, it remains to be seen if this benefit is sufficient to overcome the opportunity costs of conserving forest patches. A further difficulty revealed by our results in promoting this ecosystem service argument for forest conservation is that final fruit production (in contrast to pollen tube abundance) is not, at least in Kodagu, actually affected by either forest proximity or size. This is possibly because Kodagu is relatively well-endowed with forest cover and widely foraging pollinators such as *A. dorsata* are relatively insensitive to changes in forest patch distribution across the range of values found in Kodagu.

5 Conclusion

Tropical landscapes are often composed of remnant forests dispersed within a matrix of agricultural fields. Most studies on coffee agroforests have emphasized on distance from the forest as the most important variable on pollination services. Our study clearly shows that in a landscape with a high density of remnant forests, distance from the forests becomes less relevant. Other variables, such as size of the forest, availability of alternative floral resources and extent of coffee flowering within the landscape (following rain or irrigation), play a significant role in influencing pollination services and/or fruit production. In addition to forests, the coffee agroforests also provide nesting sites for some bees and forage. Despite the importance of agroforests as a refuge for bees, the need to conserve the remnant forests arises in the case of pollinators that preferentially nest in them. The importance of such remnants becomes even more important when the pollinator is one of the most important pollinators as in the case with *Apis dorsata* in our own study making the need to conserve these forests imminent. Since *Apis dorsata* preferentially nests on large trees found in natural habitats, the protection of such habitats becomes imperative. Additionally, augmentation of colonies of *Apis cerana indica* within coffee agroforests and retention of structures such as old stone walls (Fig. 32.4), as well as tree holes or dead tree trunks in agroforests and forest patches in which *Tetragonula iridipennis* prefers to nest, could benefit the coffee farmers in terms of enhanced pollination services. Management interventions such as irrigation can provide a farmer the benefit of a disproportionately large number of pollinators compared to agroforests that are rain-fed.

Coffee landscapes across the globe is undergoing changes as forest patches are increasingly cleared or degraded and native trees in coffee agroforests are either being removed or replaced with relatively more open canopies of exotic species (Jha et al. 2014), for example, *Grevillea robusta* in India. The relationships between forest cover, shade tree density and pollination services will likely change with the continued trend of forest and tree loss. While remnant forest patches are crucial for providing suitable nesting trees for wild species, this study also shows that there are multiple on- and off-farm factors that affect pollination and crop production and pollination services cannot be simply interpreted as a function of forest patch distribution alone. Changes in rainfall patterns (extended drought periods and reduced rainfall) in the recent decades (CAFNET 2011) further emphasize the need to retain shade trees to minimize the effects of drought. With coffee cultivation being further intensified worldwide, leading to conversion of coffee agroforests with native shade cover to lesser diverse systems, farmers will have to rely on the pollination services of bees that depend on forest remnants for forage and/or nesting.

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Appendix 1

Methods

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Chapter 33
Regulating Ecosystem Services Delivered in Agroforestry Systems

S. Kuyah, I. Öborn, and M. Jonsson

Abstract Regulating ecosystem services are the benefits obtained from the regulation of ecosystem processes. The multifunctional role of trees makes agroforestry interventions ideal management practices to supply a variety of regulating ecosystem services. This chapter reviews seven regulating ecosystem services (carbon sequestration, soil fertility enhancement, prevention of soil erosion, water regulation, wind regulation, pest regulation, and pollination) for which research in tropical and/or temperate regions have shown evidence that introduction of agroforestry practices on crop or pasture land can provide significant benefits. In each case, we provide a general description of the ecosystem service and evidence of whether this service increases or not by agroforestry practices and discuss the factors that affect the provision of the ecosystem service in agroforestry. We also discuss the multifunctionality with synergies and trade-offs among regulating ecosystem services and provide suggestions on how modifications of tree-based systems may increase ecosystem service provision. Generally, agroforestry increases delivery of regulating ecosystem services within the landscape, leading to increased growth and yields from crops and animals. However, there are situations where agroforestry may lead to a reduction in certain ecosystem services, leading to trade-offs. Trade-offs among regulating services and between regulating services and other ecosystem services are, for example, brought about by competition for water and other resources and

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increases in certain pests. We discuss how agroforestry practices can be designed in a way that reduces ecosystem service trade-offs while increasing the productivity of crops and livestock.

Keywords Carbon sequestration · Erosion control · Pest control · Pollination · Soil fertility enhancement · Water regulation · Wind regulation · Trade-off

1 Introduction

The millennium ecosystem assessment framework identifies a variety of regulating ecosystem services (ES) delivered in ecosystems (MA 2005). Regulating ES are the benefits obtained from the regulation of ecosystem processes (MA 2005). These benefits occur both as intermediate services and final benefits, meaning some do not benefit humans directly, e.g., pollination, while others provide direct benefits to humans, e.g., flood regulation (Kumar et al. 2010). Some of the ES are provided across ecosystems, while others are produced in specific ones. Most of the landscapes are managed to increase the supply of single provisioning ES such as timber in forestry or food in agriculture. However, the importance of regulating services is becoming widely recognized, and landscapes are increasingly being managed for multiple ES (Kumar et al. 2010; Harrison et al. 2014). The range of regulating ES that can possibly be delivered by incorporating trees in agriculture through different agroforestry practices, as described by Sinclair (1999), is listed in Table 33.1. The services can be provided at small scale, e.g., enhancement of soil fertility through biological nitrogen fixation, or at global scale, e.g., climate regulation through carbon sequestration (Schroth and Sinclair 2003).

The multifunctional role of trees makes agroforestry interventions good candidates for supplying multiple ES. This is underpinned by the ability of agroforestry to produce a variety of ES on the same land area as food or fodder crops while at the same time maintaining biodiversity. Biodiversity is closely linked to the functioning of ecosystems, and studies show positive relationship between biodiversity attributes and ES (Harrison et al. 2014). Although recent developments in agriculture have to some extent increased productivity, negative impacts such as loss of biodiversity and associated ES have occurred because of landscape simplification and land-use intensification (Tscharntke et al. 2005). Agroforestry provides vegetation diversity that can enhance delivery of regulating ES within agricultural landscapes. However, there are situations where agroforestry render disservices, leading to trade-offs among ES (Kuyah et al. 2016), and therefore there are prospects of optimizing agroforestry practices in the future for better multiple ES management.

In this chapter, we focus our discussion on seven important regulating ES that have received significant attention in agroforestry research in both tropical and temporal regions: carbon sequestration and storage, soil fertility enhancement, preven-

Table 33.1 List of regulating ecosystem services that can be delivered by trees through different agroforestry practices

	Ecosystem service	Description
1	Soil fertility enhancement	Trees provide nutrient inputs into the soil through litter addition and biological nitrogen fixation and prevent nutrient loss
2	Pest regulation	Agroforestry systems regulate pests, weeds, and diseases by making conditions less beneficial for them, reducing their dispersal, or through the activities of predators and parasitoids
3	Water regulation	Agroforestry systems regulate water discharge and recharge within the landscape
4	Carbon sequestration	Trees remove carbon dioxide from the atmosphere and keep it in their tissues or in the soil when they die and decompose
5	Prevention of soil erosion	Vegetation and litter provide ground cover to prevent soil loss
6	Wind regulation	Trees are used as windbreaks and shelterbelts to regulate wind speed
7	Pollination	Trees provide nesting habitat and food for insects, bats, and birds that transfer pollen from one plant to another
8	Microclimate	Trees provide shade and influence water availability locally
9	Climate regulation	Agroforestry systems regulate global climate by absorbing or emitting greenhouse gases into the atmosphere
10	Air-quality regulation	Trees absorb odors and sound, filter pollutants from the air, and release oxygen into the atmosphere
11	Water purification	Channels formed by roots of trees allow water to trickle through the soil, filtering toxins, nutrients, and sediments
12	Bioremediation of soil	Woody vegetation removes nutrients and contaminants from the soil and can use these for growth
13	Moderation of extreme events	Trees stabilize slopes and create buffers against extreme weather events such as floods, storms, and landslides
14	Regulation of human disease	Trees regulate the incidence and abundance of some pests and vector-borne diseases that attack humans

tion of soil erosion, water regulation, pest regulation, pollination, and wind regulation (Fig. 33.1). The chapter provides a general description of each of the ES, evidence of whether the service increases or not by agroforestry practices, and what factors affects ES provision in agroforestry.

In a final section, we discuss synergies and trade-offs among ES and provide suggestions on how to optimize provision of regulating ES in agroforestry. Discussions in this chapter are supported by recent review papers regarding regulating ES and modification of agroforestry practices that aim to increase ES provision (Pumariño et al. 2015; Kuyah et al. 2016).

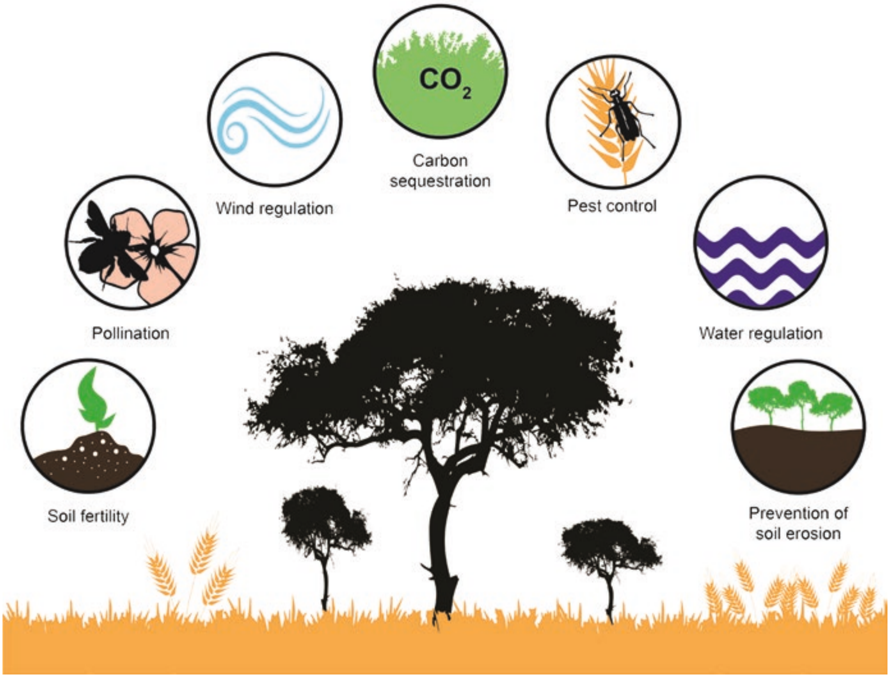

Fig. 33.1 Graphical representation of seven important regulating ecosystem services that can be affected by agroforestry practices

2 Ecosystem Services

2.1 Soil Fertility Enhancement

Soil fertility enhancement is sometimes considered as a supporting ES but more often a regulating ES. Soil fertility has been defined as the ability of a soil to serve as a suitable substrate on which plants can grow and develop (Schroth and Sinclair 2003). Improvement of soil fertility by agroforestry practices therefore relates to the positive effects of trees on the nutrient content of the soil, soil physical properties, and soil microorganisms. Declining soil fertility is a major factor limiting productivity of agricultural systems, particularly in the tropics where soils have poor organic matter and nutrient levels (Schroth and Sinclair 2003). Integration of woody perennials in agricultural landscapes can help maintain or enhance soil fertility by improving the ability of the soil to absorb and retain water, supply nutrients to plants from deeper soil layers and biological nitrogen fixation (for species having that capacity), and maintain favorable conditions for microbial activity and keeping moisture.

The review by Kuyah et al. (2016) found that 53% of studies on soil fertility in sub-Saharan Africa reported an increase in soil fertility and 9% reported a reduction, while 38% showed no effects of trees on aspects of soil fertility. Trees contribute to soil fertility by improving soil physical properties; providing biological nitrogen fixation, litter fall, and pruning; reducing loss of organic matter and nutrients by recycling nutrients and controlling soil erosion; and regulating the activities of soil microorganisms. Trees influence the soil structure by adding organic matter through litter fall and exudates in the rhizosphere and by growth of roots into deeper compacted soil layers. For example, studies in parkland agroforestry show higher soil organic matter closer to trees (Bayala et al. 2002; Pouliot et al. 2012). Buildup of soil organic matter and the growth of roots reduce soil compaction; improve soil structure, water infiltration, and water and nutrient holding capacity; and reduce soil erosion. These properties are often reported in the literature where improved soil fertility is recorded and growth and yield of crops enhanced (Kuyah et al. 2016).

Legume and some non-legume trees and shrubs have the ability to add substantial amounts of nitrogen into the soil through biological nitrogen fixation and litter fall. Improved fallows accumulate nitrogen in above- and belowground biomass, which is returned to the soil when the fallows are cleared, and the biomass is then incorporated into the soil. Foliage of trees can also be incorporated into the soil to enrich soil fertility in what is commonly referred to as green manuring. Species such as *Tithonia diversifolia* provide huge amounts of leaf biomass that has high levels of nitrogen and that decomposes easily in the soil (Rao and Mathuva 2000). The nitrogen fixed by the trees into their biomass is made available to other plants through decomposition. Even after decomposition, trees can still increase the amount of labile fractions of soil organic matter that supplies nutrients to crops (Barrios et al. 1997).

Another way through which trees increase nutrient inputs into the soil is by retrieving nutrients from the deeper soil horizons and through weathering of soil minerals and pumping nutrients into the canopy (Aweto and Iyanda 2003). When the leaves fall and decompose, the nutrients are cycled to the topsoil where the crop can absorb them. Analysis of soil characteristics under individual tree crowns in West Africa showed greater levels of soil nutrients beneath tree crowns compared to open areas (Boffa et al. 2000; Bayala et al. 2002; Takimoto et al. 2008; Pouliot et al. 2012). Trees also improve soil fertility by controlling runoff and soil erosion; they reduce losses of water, soil material, and organic matter and nutrients (Angima et al. 2002; Kinama et al. 2007; Mutegi et al. 2008).

Agroforestry also improves soil fertility by maintaining biological activity of soil microorganisms. Important microorganisms for soil nutrient management within agroforestry are those that fix nitrogen and those that solubilize phosphorus. Organic matter added to the soil provides a nutrient-rich substrate for soil microorganisms. Trees also provide favorable conditions for microorganism, enhancing decomposition of litter. For example, higher populations of earthworms, centipedes, and millipedes were reported under improved fallows compared to monoculture maize in eastern Zambia, due to amelioration of the surface soil temperature and moisture by litter and tree leaf biomass incorporated into the soil (Sileshi and Mafongoya 2006). The microorganisms in turn aid in nutrient cycling.

However, trees can also compete with crops for nutrients and reduce certain soil nutrients through nutrient uptake as compared to crop monocultures. For example, agroforestry with hedgerows had lower nutrient levels, i.e., soil nitrogen, plant available P, and exchangeable bases than crop monocultures (Mathuva et al. 1998; Kang et al. 1999; Makumba et al. 2009).

2.2 Pest Regulation

Natural pest control concerns the ability of an ecosystem to reduce the damage caused by weeds, herbivorous mites and insects, and plant pathogens. Plant diversity and composition can have a strong effect on pest control, both through bottom-up mechanisms directly affecting the pests, e.g., via resource concentration or changes in microclimate, and through top-down processes via enhancement of natural enemies or other antagonists (e.g., Rao et al. 1998, 2000; Root 1973; Landis et al. 2000). Agroforestry therefore has an obvious potential to affect natural pest control.

Kuyah et al. (2016) found that 68% of the studies from sub-Saharan Africa showed a positive effect of agroforestry on pest control (i.e., reduced pest problems), whereas 15% found a negative effect and 26% no effect. Similarly, in a global meta-analysis, Pumariño et al. (2015) found that agroforestry resulted in reduced abundances of weeds and increased abundances of natural enemies. The effects of agroforestry on invertebrate pests and plant diseases depended on crop type. Agroforestry in perennial crops (e.g., coffee and cocoa) reduced pest abundances and crop damage, while no significant effect was detected in annual crops (e.g., maize and rice).

Agroforestry influences weeds through the ability of decomposing material to modify soil properties, shading by canopies, soil cover by vegetation and litter, or allelopathic effects from root secretions (Gacheru and Rao 2001, 2005). These mechanisms can reduce weed populations, deplete weed seed banks, decay annual weed banks, or reduce viability of perennial weed rhizomes (Rao et al. 1998, 2000; Sileshi et al. 2007). Studies in western Kenya show that agroforestry practices with trees that increase inorganic nitrogen availability in the soil (e.g., *Tithonia diversifolia, Sesbania sesban*, and *Tephrosia vogelii*) reduce infestation by the parasitic weed, *Striga* (Gacheru and Rao 2001, 2005). In Zambia, improved fallows that promote vegetative soil cover were shown to reduce infestation by arable weeds (Sileshi and Mafongoya 2003). A reduction in weed abundance and a shift in the composition of weeds to less aggressive forms by shading have been noted to occur in coffee- and cocoa-based agroforestry systems (Beer et al. 1998).

Invertebrate pests are influenced by agroforestry through both bottom-up factors (microclimate, resource concentration) and top-down factors (natural enemies). The shade effect of agroforestry trees can help naturally reduce pests by modification of microclimatic conditions. For example, high shade index in the humid zones of Cameroon reduced the number of mirid bugs and cocoa pod borers and the rate of herbivory on cocoa (Daghela Bisseleua et al. 2013). One reason for reduced pest abundances under shade cover is that temperatures are lower and thus development rates are slower, as long as temperatures at both the shady and the sun-exposed sites are within the thermal range of the pests. However, light intensity, air temperature, wind speed, and humidity can also be important (Rao et al. 1998, 2000). The increased plant diversity under agroforestry management may also make it more difficult for pests to locate the crop, e.g., through modified odor and visual stimuli, and result in reduced connectivity among crop patches (Root 1973; Schroth et al. 2000; Avelino et al. 2012). Furthermore, this higher diversity of plants can provide resources for natural enemies that suppress insect pests. For example, ants (Perfecto et al. 1996; Gras et al. 2016), parasitoids (Pardee and Philpott 2011), birds (Karp et al. 2013; Gras et al. 2016), and bats (Gras et al. 2016) have been shown to reduce the abundance of arthropods in coffee- and cocoa-based agroforestry systems.

In many cases, a combination of different mechanism is probably responsible for the effects of agroforestry on pests. For example, the effects of agroforestry on the coffee berry borer *Hypothenemus hampei* may be due to a combination of improved conditions for natural enemies such as birds (Karp et al. 2013) and parasitoids (Pardee and Philpott 2011), reduced temperatures resulting in lower development rates (Jaramillo et al. 2009), changes in chemical composition of coffee berries that make them more difficult to locate for egg-laying coffee berry borer females (Jaramillo et al. 2013), and decreased connectivity among coffee trees that reduces dispersal (Avelino et al. 2012).

Agroforestry can also affect the incidence, spread, and severity of plant pathogens and diseases. Studies in high altitude regions of Africa show that shade-grown coffee has significantly reduced severity of coffee diseases compared to sun-grown coffee (López-Bravo et al. 2012). Tree species in agroforestry help control diseases primarily by modifying microclimatic conditions (Schroth et al. 2000; Sileshi et al. 2007). For example, shade trees reduce coffee blight by protecting leaves from strong winds that injure the plants and enable pathogens to penetrate. The shade from trees also reduces coffee rust attacks by regulating yields (López-Bravo et al. 2012) and can reduce coffee berry disease incidence by intercepting rainfall, reducing the splash effect of raindrops that disperses propagules (Mouen Bedimo et al. 2007).

The effect of agroforestry on pest control is however not consistently positive but can have negative effects under some conditions (Jonsson et al. 2015; Kuyah et al. 2016). For example, in Uganda, two serious insect pests have been found to thrive and cause more damage to coffee under shaded conditions in agroforestry plantations: the white stemborer *Monochamus leuconotus* (Jonsson et al. 2015) and the coffee twig borer *Xylosandrus compactus* (Kagezi et al. 2013). The effect of shade trees can be highly dependent on shade level, with too high and too low levels of shade trees both reducing the efficacy of natural enemies (Gras et al. 2016). The effects may also depend on the climatic conditions, for example, due to differences in altitude (Jonsson et al. 2015). Furthermore, in some cases, shade trees within agroforestry can enhance intra-guild predation, e.g., increased bird predation in agroforestry can also suppress beneficial insect predators such as spiders and ants which may lead to increased pest problems (Johnson et al. 2009).

Microclimatic changes induced by trees can in some cases provide better conditions for disease infection and development (Schroth et al. 2000; Sileshi et al. 2007). For example, the incidence and severity of coffee leaf rust were greater under shade than full sun coffee in Costa Rica (López-Bravo et al. 2012). In Kenya, higher incidence and severity of angular leaf spot and anthracnose were observed on beans in alleys with *Leucaena* hedgerows than on beans in plots without trees (Koech and Whitebread 2000). Studies with improved fallows in Kenya showed that the benefits of agroforestry practices may be compromised by plant-parasitic nematodes when the agroforestry tree is an alternative host (Kandji et al. 2003).

2.3 Water Regulation

Water regulation relates to alteration of the amounts of water available locally. Components of agroforestry systems modify variables that regulate water availability through interception, transpiration, infiltration, surface runoff, and soil evaporation (Cannell et al. 1996; Ong et al. 2006). Water regulation in agroforestry is partly influenced by stomatal response to water vapor deficit and irradiance, two factors that are strongly affected by modification of microclimate. The influence of agroforestry practices on water availability depends on the climatic conditions and the type of tree and crops planted.

Water regulation was the second most frequently reported regulating ES in agricultural landscapes of sub-Saharan Africa, where 51% of studies reported a positive effect of trees, 35% found a negative effect, and 14% showed no effect (Kuyah et al. 2016). Trees improve local water availability by positively affecting groundwater recharge through enhanced infiltration. A systematic review and meta-analysis showed increased soil infiltration rate after tree planting across a wide range of rainfall conditions (Ilstedt et al. 2007). In studies comparing tree-based systems and monocultures or open spaces, trees enhanced infiltration in dispersed intercropping systems in Kenya (Jackson et al. 2000) and improved legume fallows in Zambia (Chirwa et al. 2004), parklands of West Africa (Boffa et al. 2000; Sanou et al. 2010), coffee-based agroforestry in Mexico (Cannavo et al. 2011), buffer strips in Missouri, USA (Anderson et al. 2009), and pasture systems in Central America (Benegas et al. 2014). Improved infiltration is attributed to improved soil hydraulic properties (Ilstedt et al. 2007), through channels that allow water to percolate down through the soil profile.

Trees also improve local water availability by controlling evapotranspiration from understorey plants and the soil. The canopies of trees have been shown to effectively reduce transpiration and evaporation from understorey plants and the soil beneath (Jackson and Wallace 1999; Jackson et al. 2000). This is primarily attributed to a decrease in temperatures beneath the trees and reduced air movement through the understorey environment (Cannell et al. 1996). By regulating microclimate, tree canopies influence the amount of radiant energy reaching understorey crops or the soil, so that less solar energy is used to evaporate moisture from the leaves of plants and the soil in areas without trees compared to tree-based systems.

However, there are situations where trees negatively affect water availability in different agroforestry practices. First, some of the water taken up by the trees is lost through transpiration. Losses from trees are obviously greater than losses from understorey plants (Anderson et al. 2009; Cannavo et al. 2011). Second, water uptake by trees can have negative effects depending on the climatic conditions, the type of tree species involved, the spatial arrangement, density, and management (e.g., pruning of roots or branches). This is a particular problem in semiarid areas during the dry season, in landscapes with infertile or shallow soils, or where trees with extensive roots near the surface are grown (Rao et al. 1998; Ong et al. 2006). In such conditions, the negative effects of competition for available resources between trees and crops often outweigh the benefits.

2.4 Carbon Sequestration

Carbon sequestration involves the removal of carbon from the atmosphere and subsequent storage into vegetation; the carbon is transferred into the soil when the trees die and decompose forming soil organic matter. Carbon is held in live vegetation as above- and belowground biomass, in dead wood, in litter, and in the soil. When trees are cut down and burned and the soil is tilled, the carbon stored is released back into the atmosphere, increasing atmospheric carbon dioxide (CO_2) concentration, a major contributor to the greenhouse effect responsible for global warming.

Carbon sequestration was documented as the fourth most commonly reported regulating ES in agricultural landscapes of sub-Saharan Africa, after soil fertility enhancement, water regulation, and pest control (Kuyah et al. 2016). Due to the spatial extent of agricultural landscapes, trees in such landscapes store huge amounts of carbon (Zomer et al. 2009). The duration carbon is stored in the systems can be prolonged by increasing the harvesting intervals and by conversion of harvested wood into durable products, e.g., sawn wood for use in buildings. Harvested wood products are considered a significant sink of carbon by the Intergovernmental Panel on Climate Change (IPCC) and considerably delay the release of CO_2 emissions to the atmosphere (IPCC 2006).

Scientific evidence shows that agroforestry practices in agriculture sequester larger amounts of carbon than monoculture field crops or pastures (Makumba et al. 2007; Takimoto et al. 2008; Gupta et al. 2009; Saha et al. 2009). The carbon sequestered in agroforestry depends on the type of practice, its components (species), arrangement and density, age, and environmental conditions – which vary across agroecological zones (Nair et al. 2009). For example, woodlots with mature trees stock more carbon in aboveground biomass compared to dispersed planting, live fence, and fodder banks (Takimoto et al. 2008). An overview by Jose (2009) shows that agroforestry systems on fertile soils or in humid zones have higher carbon stocks than those on degraded soils or in arid and semiarid zones and that vegetation in temperate agroforestry systems has lower carbon storage potential than those in the tropics.

2.5 Prevention of Soil Erosion

Soil erosion wears away the topsoil by water, wind, and tillage and relocates it elsewhere. Some of the negative effects of soil erosion include reduced productivity of the soil, destruction of crops, and pollution of water resources through sedimentation and eutrophication. Land use and vegetation cover are the most important factors that determine the intensity of erosion in a given place, although the intensity of rainfall, the soil texture, and the gradient of the slope play an important role too (Schroth and Sinclair 2003). Integration of woody perennials in farming systems as contour hedgerows, often combined with grass strips (e.g., Angima et al. 2002), can help control soil erosion.

Seven out of nine studies investigating erosion control in the review by Kuyah et al. (2016) reported positive effects of trees on soil erosion control, whereas two studies showed no significant effect. Trees alone or combined with terracing and other physical measures can bind the soil together and prevent water erosion. For example, hedgerows with *Calliandra calothyrsus*, *Senna siamea*, and *Leucaena trichandra* effectively reduced surface runoff on slopes in central Kenya (Angima et al. 2002; Kinama et al. 2007; Mutegi et al. 2008). Runoff was also reduced in coffee systems with *Inga densiflora* compared to coffee monoculture in Costa Rica (Cannavo et al. 2011). A recent meta-analysis shows that European agroforestry practices significantly reduce surface runoff of soil (Torralba et al. 2016). There are several mechanisms by which agroforestry practices reduce runoff and erosion. Most importantly, trees provide a protective cover (tree canopy, understorey, and litter) that reduces the impact of raindrops and associated erosion. Experiments in rubber-based systems show that rain falling on bare soil in the open cause splash and to a larger extent can initiate sheetwash compared to rain falling on vegetation (Liu et al. 2016). Secondly, trees create a barrier that reduce runoff velocity, arrest sediments, and allow more time for the water to infiltrate into the soil. On the contrary, crop monocultures have high soil erosion because of reduced rainfall interception and lower water retention and storage. In addition, monocultures are characterized by reduced infiltration and water in excess of the amount required by crops (Ong et al. 2006; Anderson et al. 2009).

2.6 Wind Regulation

Wind regulation includes reduction of wind speed and redirection of the wind in the landscape, e.g., by incorporating trees. Reduction of wind speed has potential benefits such as reduced evapotranspiration and increased water use efficiency of crops (Benzarti 1998). In arid and semiarid environments, using trees to regulate wind reduces the turbulent transfer of heat and water vapor, resulting in moderated soil and air temperature, increased humidity, increased soil moisture, and reduced evaporation. Wind regulation by agroforestry practices also helps prevent wind erosion, for example, by creating a semipermeable barrier that reduces the ability of wind to carry objects (Brandle et al. 2004).

Trees and shrubs planted in suitable configurations (e.g., hedgerows or boundary planting) can be used as windbreaks or shelterbelts to reduce erosion, protect livestock from heat and cold, and protect crops, water resources, and settlements from strong winds (Brandle et al. 2004). Strong winds can cause mechanical damage, wither crops, transport sand to crop fields, or generally limit agricultural productivity of an area. The effectiveness of windbreaks depends on their structure, for example, height and density, length and orientation, and their location within the landscape (Brandle et al. 2004).

In sub-Saharan Africa, four studies have shown that the presence of trees in the landscape positively influences the dynamics of wind, leading to improved crop yields compared to unprotected fields (Kuyah et al. 2016). For example, studies with hedgerows show that wind speed was reduced under hedges compared to in open fields (Benzarti 1998). Trees such as *Vitellaria paradoxa* and *Parkia biglobosa* scattered throughout the fields such as in the parklands of West Africa have been shown to break up wind patterns (Jonsson et al. 1999). The negative effects of trees for wind regulation are declines in other services because of the presence of the trees, and these are discussed in Sect. 3 under trade-offs.

2.7 Pollination

Pollination is the transfer of pollen grains from the male anther of a flower to the female stigma. Flowers rely on visiting insects and animals (pollinators) and wind to transfer pollen. Pollination as an ES in agroforestry therefore relates to the role of trees in regulating the incidence and spread of pollinators. Bees are the most important pollinators in agroecosystems; other pollinators include insects such as beetles, wasps, butterflies and flies, birds such as hummingbirds, and bats. Most of these pollinators are threatened by habitat loss and fragmentation, environmental contaminants such as pesticides, and higher incidences of pests and diseases (Potts et al. 2010). For example, coffee farms close to remnants of tropical forests have been found to have higher levels of coffee pollination resulting in significant economic benefits of preserving trees and forest habitat (Ricketts et al. 2004). Agroforestry practices can promote the diversity and abundance of pollinators by reversing habitat loss, increasing habitat connectivity, and reducing use of agrochemicals.

Agroforestry has potential to enhance pollination services by providing essential habitat and food for pollinators and favorable conditions for pollinator activities. No studies on the effects of agroforestry on pollination in sub-Saharan Africa were found in the review by Kuyah et al. (2016); however, studies exploring the effects of trees on pollination are available from various other temperate (Varah et al. 2013) and tropical regions (e.g., Ricketts et al. 2004; Boreux et al. 2013). Most agroforestry practices already include insect-pollinated plants that provide nectar for pollinators and patches of uncultivated ground and snags (standing dead trees and branches) for nesting. These conditions are often lacking in monoculture crops and pastures (Hoehn et al. 2010; Varah et al. 2013); monocultures are characterized by seasonal bloom and shortage of pollen and nectar resources. Agroforestry also modifies the microclimate, providing favorable conditions for pollinator activity. Varah et al. (2013) reported relatively high pollinator species abundance and diversity in silvoarable agroforestry systems compared with monocultures in the UK. Similarly, cacao agroforestry systems in Sulawesi showed higher bee diversity and density than primary forests at local scale and higher bee richness in agroforestry compared to open land and primary forests at regional scale (Boreux et al. 2013). Agroforestry affects the availability of pollinator habitat through its effect on shade at local scale (Klein et al. 2002) and habitat connectivity at landscape scale (Kasina et al. 2009).

However, the effect of agroforestry on microclimate, such as high humidity, can in some cases cause negative effects on pollinators. In addition, intensively managed agroforestry systems may in some cases harbor less pollinator diversity than monocultures or open areas. For example, local bee density and diversity were higher in open land than in agroforestry plantations because of abundance of herbaceous food resources (Hoehn et al. 2010).

3 Synergies and Trade-offs

Ecosystem services described in this chapter are not only delivered simultaneously with provisioning and supporting ES but also with other regulating services. This means that trees in different agroforestry practices deliver multiple ES, regardless of the reason for which trees are planted or maintained in the landscape. Examples of provisioning of multiple regulating services are where farmers have planted fodder trees and shrubs along contour lines on slopes to stabilize the soil and control soil erosion, but the trees also improve soil fertility through biological nitrogen fixation and litter inputs. Similarly, shade trees integrated in perennial crops such as coffee and cocoa may be aimed at moderating microclimate but also regulate water availability and the dynamics of pests. The following section describes synergies among regulating ES using changes in microclimate and their effects as examples. Thereafter trade-offs among selected regulating ES delivered in agroforestry are reported.

For the majority of regulating ES, the effects of trees on crops are at least partly mediated by changes in microclimate. In the tropics, trees improve microclimate by shading and depending on climate and crop may provide better conditions for the growth of plants beneath trees. Areas close to trees tend to have reduced light levels, lower temperatures, and higher relative humidity, conditions associated with improved growth and yield of crops in semiarid tropics (Kuyah et al. 2016). Studies show that shaded coffee systems have lower air temperature compared to monocultures (López-Bravo et al. 2012) and that silvopastoral systems with trees have reduced fluctuations in temperature, increased minimum temperatures at night, and reduced maximum temperature during the day compared to those without trees (Silva-Pando et al. 2002). These conditions are associated with improved grass or crop yields, improved soil fertility from addition of litter and better conditions for decomposition, and high soil moisture because of reduced evapotranspiration (Boffa et al. 2000; Pouliot et al. 2012; Sanou et al. 2012). Studies report situations where agroforestry increased two or more ES simultaneously: in Kenya *Senna spectabilis* hedgerows improved both microclimate (by reducing evapotranspiration) and yields of maize and cowpea (Mclntyre et al. 1997); *Leucaena trichandra* and *Calliandra calothyrsus* hedgerows reduced soil erosion and increased crop yield but did not influence soil fertility (Mutegi et al. 2008). Trees in silvopastoral systems protect animals from strong winds and provide shade during hot weather or midday sun in arid and semiarid zones.

Trade-offs occur when the benefits of trees are increasing the delivery of one ES but decreasing another. This has, for example, been reported in situations where trees reduce ES through depletion of water available for crops, depletion of nutrients, excessive reduction in light reaching crops, and stimulation of certain pests and diseases (Kuyah et al. 2016). Benefits of trees related to soil fertility are common in humid and subhumid zones, where yields are increased by improvement in soil fertility but might be marginal in water-limited environments except when the trees are managed to reduce competition. For example, despite improvement in soil fertility (increased soil organic carbon (SOC) and available phosphorus) in semiarid areas, lower crop yields were recorded in the first year of a *Gliricidia sepium*-maize intercrop (Akinnifesi et al. 2006), under high density of *Vitellaria paradoxa* intercropped with sorghum (Boffa et al. 2000) and under *Acacia senegal* intercropped with sorghum and roselle (El Tahir et al. 2009). Trees used for improving soil fertility in crop fields or alley cropping systems, or those used for wind regulation or shelterbelts to control wind speed, can increase problems with certain pests and diseases. For example, in Senegal, dispersed planting of *Piliostigma reticulatum* improved soil fertility but increased population density of Hoplolaimidae and Dolichodoridae nematodes in pearl millet (Diakhaté et al. 2013). In Kenya, crop yield under *Sesbania sesban* and *Crotalaria grahamiana* increased due to improved soil fertility, although these tree species were found to increase the population of nematodes in beans and maize, respectively (Desaeger and Rao 2000). Stimulation of pest and disease problems may occur if the trees used are host plants for agricultural pests, when the trees harbor predators of beneficial insects, and when modified microclimate provides better conditions for pests and diseases.

4 Management of Agroforestry to Enhance Provision of Ecosystem Services

Productivity of agroforestry practices depends on the type of trees and crops planted and the way they are managed. Agroforestry practices can be productively adapted to agricultural landscapes by selecting suitable tree-crop combinations and appropriate management of the trees. Productive agroforestry practices ensure provisioning services such as fiber, food, fodder, and fuel without reducing crop yields. Agroforestry can also be designed and managed to effectively control soil erosion; improve soil fertility; reduce damage by weeds, insect pests, and diseases; and enhance pollination services and at the same time minimize trade-offs. This can be achieved by optimizing positive effects and minimizing negative effects that arise from competition for resources (water, nutrients), shading (light), and avoiding trees that are hosts for pests and diseases and by reducing allelopathic effects of trees.

Agroforestry practices can be modified to improve water- and nutrient-related benefits of trees and avoid losses in crop yields. This can be achieved by planting trees with suitable rooting architecture or phenology to ensure complementarity with the crop (Ong et al. 2006). In systems with trees and arable crops, deep-rooted trees are preferable because of their ability to use resources in the deeper soil layers, while shallow-rooted crops exploit resources in the upper soil profile (Cannell et al. 1996). Tree phenology is important for reducing competition for water resources and shading. Deciduous trees tend to have a reduced demand for water relative to evergreen species, particularly in the dry season when water supply is limited (Kho et al. 2001).

The canopy of trees should permit enough light to reach understorey crops to minimize negative effects of shading on yields and quality. This is particularly important when growing shade-intolerant crops, such as cereals, compared to shade-tolerant crops such as chili pepper (Pouliot et al. 2012). Benefits have been reported when using *Faidherbia albida,* a tree that locally shed leaves in the wet season and that has full foliage in the dry season, providing shade for livestock, plants, and the soil (Kho et al. 2001). Competition for light can also be minimized by orienting trees in the landscape in a way that maximizes sunlight within the canopy and reduces shading to adjacent trees or crops. This is feasible where the ground is flat; slope and soil type should be considered on land that is not flat.

Optimal spacing and pruning (above and below ground) ensure that agroforestry practices provide better growing conditions for crops and improve provision of other ES. While increasing the number of trees in the field can increase tree products, the benefits begin to decrease as the trees mature and become crowded. It is important to determine the appropriate arrangement and density of trees on crop or pasture land, depending on prevailing edaphic and climatic conditions. Pruning can be conducted to reduce water demand of the trees and to minimize the negative effects of shading. Depending on the purpose for which the trees are planted, side pruning, lopping, pollarding, coppicing, and thinning can be used to reduce shade for crops near the tree, to improve the quality of tree products (e.g., timber and poles), and to reduce the tree density.

Enhancing pest control in tree-based agricultural systems requires appropriate manipulation of those factors that determine the dynamics of pests and their natural enemies and includes tree species, planting arrangement, and management of the trees in the landscape. Aspects related to the choice of tree species include introduction of odoriferous plants that can either repel or attract pests, whereas host plants of pests should as far as possibly be avoided. Trees can be planted to provide habitat and food for natural enemies. For example, trees that are flowering at the right time can attract omnivorous natural enemies to the crop and enhance their fitness. In cases where pests benefit from improved microclimate through agroforestry practices, shading can be reduced, e.g., through pruning.

Pollination services can be enhanced by protecting flowering plants and nest sites from disturbance and pesticides, e.g., by leaving patches of undisturbed ground and snags, minimizing tillage, and reducing use of insecticides. Agroforestry practices can be managed to add more flowering plants and nesting habitat for pollinators. This may include integrating flowering trees and shrubs such as *Caesalpinia decapetala* and *Tithonia diversifolia* in hedgerows (Kasina et al. 2009; Mwangi et al. 2012) or by incorporating legumes and other understorey flowering plants such as forbs in silvopastoral systems (Varah et al. 2013). Rotational grazing practices can be used to allow understorey plants in silvopastoral systems to recover from grazing (Varah et al. 2013). Agroforestry systems can also be designed to ensure continuous bloom. This can be achieved by planting (e.g., in alley cropping) a mix of plants with overlapping blooming times so that flowers are available to forage throughout the year. Management practices such as irrigation can also be used to induce flowering; agroforestry systems that flower asynchronously via irrigation have significantly higher bee abundance than those that flower concurrently following rains (Boreux et al. 2013).

5 Conclusions

This chapter reviewed seven regulating ES for which research in tropical and/or temperate regions have shown evidence that introduction of agroforestry practices on crop or pasture land can provide significant benefits: carbon sequestration, soil fertility enhancement, prevention of soil erosion, water regulation, wind regulation, pest regulation, and pollination. The supply of regulating ES within agroforestry is strongly influenced by its components and the climatic conditions. Overcoming trade-offs among ecosystem services remains an issue and should be addressed by well-designed practices that allow for spatial and temporal complementarity. A limitation to assessing trade-offs and synergies is that multiple ES are rarely studied, and in many cases, we don't know about the mechanisms why certain ES increase or decrease in agroforestry. Consideration of trade-offs are required to evaluate outcomes of agroforestry on multiple ES and for targeting management interventions that enhance multifunctionality.

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Chapter 34
Challenges and Strategies to Address Food and Livelihood Security in Agroforestry

Reeta Mishra and Yagya Dev Mishra

Abstract Agroforestry combines agriculture and forestry to generate integrated and sustainable land-use systems. It can be regarded as one potential solution in meeting the needs of the society and is influenced by many socioeconomic factors. These factors and their relationship to the agroforestry are highly important as this would help to ascertain the opportunities for the development of agroforestry system. The main socioeconomic factors that determine the actual occurrence of agroforestry are gender, household security, availability of planting materials, shelf life of forest products, access to market, information, and low income. A clear understanding of the influential factors in farmer's decision-making related to the adoption and maintenance of agroforestry is important.

Agroforestry is a viable option for ensuring food and livelihood security by its multiple services. Homegardens are among the best solutions of household food security and income generation. By growing different nutritious fruits and vegetables in their homesteads, families can have access to all essential nutrients throughout the year. This will go a long way to ensure that their children have a healthy diet**.** Processed and value-added forest products have the potential to improve livelihoods of poor farmers. Availability and accessible credit facilities to farmers enhance production improvement by easily accessing the required inputs at right times. Extension helps to empower and motivate rural community to enhance and diversify the productivity of their agroforestry systems and in strengthening their capacity to seize market opportunities. Thus, agroforestry can enhance the socioeconomic livelihood of rural people by enhancing food and nutritional security and income-earning potentials. Benefits may take long to make impact, but there is long-run profitability.

Keywords Agroforestry · Homegardens · Food security · Livelihood security · Value addition

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1 Introduction

Agroforestry can be regarded as one potential solution in meeting the needs of the society and has long been recognized as sustainable development model throughout the world due to the benefits it brings not only to the economy and society but also to the ecosystem (Thanh 2005; Bargali et al. 2009). Agroforestry systems are most extensive in developing countries where approximately 1.2 billion poor people depend directly on a variety of agroforestry products and services (IPCC 2000; Kittur and Bargali 2013). The World Bank estimates that over 1.2 billion people derive their livelihoods from agroforestry systems (World Bank, FAO and IFAD 2009).

In India, the current approximate area under agroforestry is estimated to be 25.31 m ha or 8.2% of the total geographical area of the country (Dagar et al. 2014; Dhyani 2014). Based on the data from CAFRI, Jhansi, and Bhuvan LISS III, the area under agroforestry is reported to be 13.75 m ha (Rizvi et al. 2014). However, Forest Survey of India estimated the same as 11.54 m ha, which is 3.39% of the geographical area of the country (FSI 2013).

Agroforestry combines agriculture and forestry to generate integrated and sustainable land-use systems. Agroforestry takes advantage of the interactive benefits from combining trees and shrubs with crops and/or livestock production. The trees ameliorate the effects of climate change by helping to stabilize erosion, improving water and soil quality, and providing yields of fruit, tea, coffee, oil, fodder, and medicinal products in addition to their usual harvest (Mercer 2004). Agroforestry promotes favored species such as fruiting trees, often with a higher nutrient content than the surrounding vegetation (Miller and Nair 2006). Women farmers are an integral part of agroforestry, as they are often responsible for managing trees especially at the early stages of establishment (Kiptot et al. 2014). They are also the primary users of various forest products from fuel wood collection to the knowledge about the medicinal value (Ahlawat and Hasumati 2009).

Like other innovative adoptions, the incorporation of trees on-farm in the form of agroforestry is a complicated process that is influenced not only by physical factors but also by many socioeconomic factors (Malla 2000; Neupane et al. 2002). Socioeconomic study of farmers and their relationship to the agroforestry is highly important as this would help to ascertain the opportunities for the development of agroforestry system (Irshad et al. 2011).

A clear understanding of the influential factors in farmers' decision-making related to the adoption and maintenance of agroforestry is important. Generally, it should be stated that the socioeconomic conditions are usually hard to identify and assess, as they are related to the human beings and their characteristics, which usually differ widely within the same community and from one community to another (Rai et al. 2006). Age is another factor that has been extensively considered as a socioeconomic factor influencing adoption of agroforestry (Ajayi et al. 2003). Other studied factors include membership in farmers' clubs and cooperative groups, availability of labor supply, and the degree of innovativeness of individual farmers.

2 Challenges for Agroforestry in Supporting Food and Livelihood Security

2.1 Gender Challenges

The differences in adoption of agroforestry between men and women, and male- and female-headed households, are often linked to their variations in accessing and controlling related resources. In general, despite women's important role in agroforestry, they remain disadvantaged due to cultural, sociological, and economic factors (Kiptot and Franzel 2012). Also, the different roles men and women play in a community can hinder the adoption of agroforestry if they are not considered in advance (Glover et al. 2013).

For women's income, agroforestry value chains are particularly important, but low access to capital, technology, and information constrain women from developing their enterprises further (Degrande and Arinloye 2014). Tables 34.1 and 34.2 show the male-female gap in literacy rate and distribution of enterprises by gender of owner.

2.2 Food and Nutritional Insecurity

Agroforestry systems with agriculture crops, trees, and livestock farms generate wide range of social and environment benefits to 1.2 billion people for enhancing food production (Jamnadass et al. 2013). Beckford et al. (2011) reported that food

Table 34.1 Literacy rate (%) and gender gap in India – 1951–2011

Census year	Males	Females	Male-female gap in literacy rate
1951	27.16	8.86	18.30
1961	40.40	15.35	25.05
1971	45.96	21.97	23.98
1981	56.38	29.76	26.62
1991	64.13	39.29	24.84
2001	75.26	53.67	21.59
2011	82.14	65.46	16.68

Source: Census of India (2011)

Table 34.2 Percentage distribution of enterprises by gender of owner in rural and urban areas

Area	Female	Male
Rural	15.27	84.73
Urban	12.45	87.55
All	13.72	86.28

Source: MSME annual report 2011–12, Ministry of MSME, Government of India security is a condition where all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life.

Solving the problem of food and nutritional security requires among other interventions a range of interconnected agricultural approaches, including improvements in staple crop productivity, the bio-fortification of staples, and the cultivation of a wider range of edible plants that provide fruits, nuts, vegetables, etc., for more diverse diets (Frison et al. 2011). As well as directly providing edible products, agroforestry trees support food production by a range of other means, including by providing shade and support for crops that need it, supporting animal production, and improving soil fertility. Agroforestry has an important role in increasing the yields of vegetables that, with fruit, provide varied and nutritionally balanced diets rather than calories alone (Susila et al. 2012).

2.3 Nonavailability of Planting Materials

Lack of planting materials (seed and seedlings) is another factor considered to constrain establishment of fallows (Peterson 1999; Kwesiga et al. 2003). Sometimes seeds and seedlings have not been sufficient to meet the needs of the farmers, or the preferred species have not been available. Generally, lack of planting materials is a limitation to adoption of agroforestry (Kwesiga et al. 2003).

2.4 Losses of Perishable Agroforestry Products

Many agroforestry products have a very short shelf life, particularly fruits and vegetables, which are mostly collected and marketed by women. For perishable goods such as fruit, the result is also high wastage along the supply chain and a failure to reach quality grades. Ramathani (2002) and Kadzere et al. (2006) reported that postharvest handling and transport are the major causes of losses of perishable agroforestry products.

2.5 Lack of Credit Facilities and Reliable Markets

Unreliable markets of their produce lead them to sell their produces by farm gate prices. These resulted into low earnings and food insecurity (IFAD 2012). For many tree products, markets are poorly structured and coordinated (Roshetko et al. 2007). This results in low and unstable returns to farmers and high prices for buyers of tree foods, which limits their consumption.

2.6 *Lack of Awareness and Technical Knowledge*

Unawareness and lack of education, technical skills, capital, technical assistance, and interest are the main hindrances in the adoption of agroforestry. As local knowledge and management originates from farmers' direct observations of nature processes and its influence on the crops, the explanation of the techniques and the process itself is not always known.

3 Measures to Overcome Food and Livelihood Security in Agroforestry

The livelihood improvement through natural resource management seeks to understand individual or household strategies through which they make long-term progress toward a better quality of life (Pretty et al. 2003; Campbell and Sayer 2003). Agroforestry is a land-use system that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop/animal production field to benefit from the resultant ecological and economical interactions (Chaturvedi and Krishnan 2009). Adoption of agroforestry practices by farmers can improve crop and livestock production (Parwada et al. 2010).

In response to both environmental concerns and the need to ensure the sustenance of livelihoods, there are many examples where agroforestry is advocated as a potential solution to the need to develop a more sustainable form of land use that improves farm productivity while, at same time, improving the welfare of the community (Roshetko et al. 2013; Leakey et al. 2012; Ahmed and Rahman 2000). Agroforestry can be more financially profitable to local farmers than traditional monoculture systems and support the transition to permanent cultivation (Rahman et al. 2014; Franzel and Scherr 2002; Predo 2002; Mai 1999).

3.1 *Gender Equality Census of India (2011), Government of India Publication, New Delhi*

Kiptot and Franzel (2012) add that the difference in decision-making authority between men and women in the family is an important determinant for the adoption of agroforestry practices by both men and women. Women are also known to be principal holders of knowledge and managers of traditional homegardens and make up about 60% of the practitioners of innovative agroforestry practices such as domestication of indigenous fruit trees and production of dairy fodder. Thus, the knowledge women have about trees, and of tree genetic diversity, and their roles as both suppliers and users of tree germplasm and genetic resources make them critical agents in scaling up agroforestry practices to improve livelihoods (World Bank, FAO and IFAD 2009).

Women may not be interested in many "cash crops," because they know they will not control the income generated. Helping women improve incomes from enterprises considered to be in womens' domains may be of more interest and benefit to them (Christoplos 2010).

3.2 Food Security through Agroforestry

Woody perennial-based production systems, such as agroforestry, have the potential to meet the food security of people. Farmers depend more on annual crops. The small and marginal farmers in the tropics have long been practicing agroforestry to meet their food, fodder, and fuel requirements (Kumar 2006). Apart from ensuring food production, such systems also would enhance economic returns to the growers.

The diverse products (fruits, vegetables, spices, etc.), which are available year-round in systems such as homegardens, not only contribute to food security during the "lean" seasons but also ensure food diversity (Kumar and Nair 2004). They are also sources of mineral nutrients for improving household nutritional security especially for at-risk populations (e.g., women and children).

3.2.1 Homegardens for Household Food Security

Homegardens can serve as models for the design of improved agroforestry practices (Kumar and Nair 2004). These gardens are highly diverse and have many functions (Fig. 34.1). Homegardens are among the best solutions of household food security and income generation to smallholder farmers due to their diversity (Kebebew et al. 2011; Lulandala 2011). The contribution of agroforestry homegardens to household food security and income generation has been affected by different factors including the homegarden productivity, shortage of irrigation water, incidence of pests and diseases, markets, and lack of extension services (Mariro 2009).

By growing several species of indigenous and exotic vitamin-rich fruit trees around their homesteads, families can have access to fresh fruits year-round. This will go a long way to ensuring that their children have a healthy diet. Guuroh et al. (2011) reported that agroforestry homegardens improve the family's nutritional status, health, and food security. Agroforestry homegardens, therefore, are part of a household livelihood strategy and have gained prominence as a natural asset through which sustainable use of resources, particularly for the livelihoods of the poor, may be achieved.

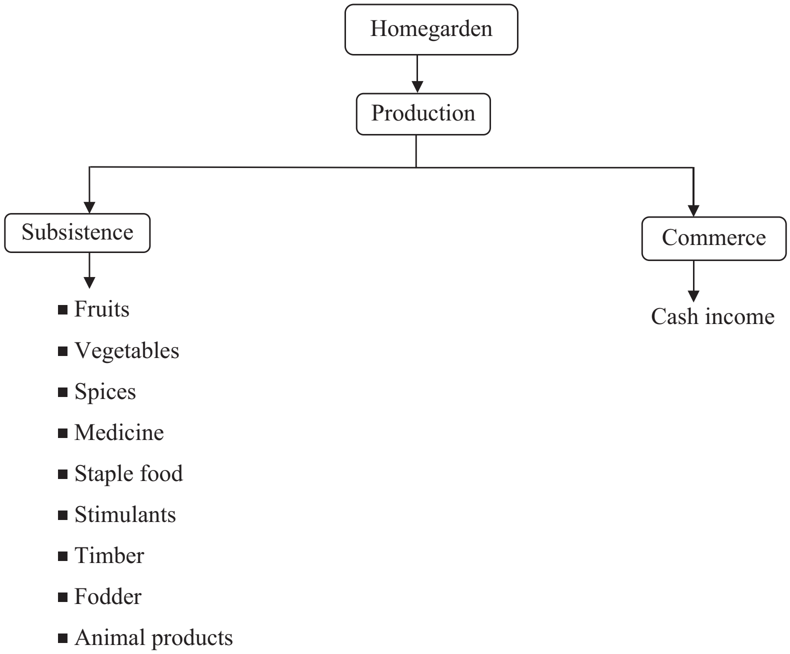

Fig. 34.1 Main functions of homegardens (Source: Kehlenbeck et al. 2013)

3.3 Nursery Development

Training and participatory nursery development are proven methods of building farmers' awareness, leadership and technical skills, and independence regarding germplasm quality, production, and management capacity (Koffa and Garrity 2001; Carandang et al. 2006).

3.4 Development of Post-harvest Storage Methods

The problem of limited shelf life can be addressed through processing which ensures supplies for periods of shortage and can improve product quality. Development of efficient agricultural and processing techniques also needs to be accompanied by capacity building.

3.5 Value Addition

Agroforestry offers ample opportunities of value addition at any time between production and harvesting to sale of the final product through a variety of services or processes like cleaning, cutting, sorting, grading, packaging, smoking, drying, freezing, extracting, or preserving. There is a need of increase in value addition infrastructure for this purpose (Bosma et al. 2003). Forest products have the potential to improve livelihoods of poor farmers, but efforts are needed to provide knowledge on the on-farm value addition innovation.

3.6 Accessibility to Markets

Availability and accessible credit facilities to farmers enhance production improvement by easily accessing the required inputs at right times (Mrindoko 2012). Doward et al. (2008) reported that provision of subsidy fertilizers improves the production quantities of farmers and hence livelihood sustainability.

Agroforestry systems can provide cash income through production of marketable goods. The prices on the market must be favorable and attractive to the farmer. This does not only mean that prices must be high enough to secure a profit margin but also that prices must be stable.

3.7 Accessibility to Information

Because the marketing aspects are also important to the farmer, he also needs to have access to information about the market (e.g., prices, demand and supply, expectations). A farmer will not decide to change his production system unless he sees the security of marketing possibilities. Farmers are not likely to be interested in producing commodities if transport costs are high. They will also be reluctant to make or continue investments in agroforestry if prices fluctuate widely (Carter 1995).

Agroforestry systems can also provide benefits through reducing the cost of purchased inputs, labor, or period to use the land again. For example, nitrogen contribution through the use of leguminous woody species in alley cropping systems with rice is less costly, despite higher labor requirements, than using chemical fertilizers (Montambault and Alavalapati 2005). In regions where the nonfarm economy is growing and population density increasing, then agroforestry systems with low requirements become interesting particularly as they provide a buffer during transition from a farm economy to a cash one (Glover and Lawrence 2010).

3.8 Accessibility to Extension Services

Extension helps to empower and motivate farmers to enhance and diversify the productivity/profitability of their agroforestry systems and in strengthening their capacity to seize market opportunities, both existing and developing (Buyinza and

Wambede 2008). Glover et al. (2013) mentioned that awareness must be created by extension services about research on issues such as tree enterprise development and tree-product marketing enhancement.

To ensure that extension services benefit women, deliberate gender sensitive interventions need to be put in place (Kiptot and Franzel 2012). Information and communication technologies can be an important tool in meeting women's basic needs and can provide the access to resources to lead women out of poverty (Lal et al. 2004). The possibility for expanding agricultural diversity is worthy, but more work is needed to improve the quality of delivery of programs through faculty skill upgrading, options for experiential learning, and further development in learning materials (Chakeredza et al. 2009).

4 Livelihood Security: Comparison in Traditional and Commercial Agroforestry Systems

In the traditional agroforestry systems since the trees are naturally growing especially in traditional agroforestry region and are just allowed to be thriving by the farmers, the costs associated with management of the trees are negligible except that of indirect costs associated with the shade and competition due to moisture and nutrient needs.

Although traditional agroforestry seems less promising as compared to commercial agroforestry, but it is also relevant to the farmers. Both the systems will be helpful for farmers' livelihood (Table 34.3).

5 Land-use Pattern in Agroforestry System for Sustainable Livelihood

Agroforestry can play a major role in bringing the desired level of diversification along with sustainability. The farm industry linkages have also helped the systems to be more sustainable than the traditional cropping systems (Kareemulla et al.

Table 34.3 Determinants of traditional vs commercial agroforestry systems

Traditional agroforestry system		Commercial agroforestry system	
Major reason	Percentage (%)	Major reason	Percentage (%)
Additional income	71.3	Fuel wood	50.6
Source of money in emergency	17.5	Additional income	24.4
Source of fuel wood	2.5	Shade	17.5
Source of employment	4.4	Timber	3.8
Others	4.4	Others	3.8

Source: Dwivedi et al. (2007)

2005; Saxena 2000). Various patterns of agroforestry systems are practiced in different agroecological regions of India which reflects biophysical and social variations. Trees are planted on the borders or within the field, systemically or at irregular intervals, usually with crops such as rice, wheat, pulse, jute, oilseed, sugarcane, vegetables, and others, and farmers also grow shade-tolerant crops such as turmeric, ginger, and aroid when trees have high canopy coverage (Miah et al. 2002). Agroforestry also has potential to contribute to the maintenance of biodiversity in natural systems due to the reduction in overreliance of rural communities on natural forest resources, as they can maintain their production systems through improved agroforestry systems.

A wider adoption of agroforestry encompasses a variety of agroforestry systems like agri-silvi system, agri-horti system, agri-pastoral system, agri-silvopastoral system, agri-horti- silvopastoral system, agri-horti-pastoral system, and agri-silvi-horti system (Pandey 2007; Islam and Sato 2010). All these alternative land-use agroforestry systems have the potential to enhance soil fertility, reduce erosion, improve water quality, enhance biodiversity, increase aesthetics, and sequester carbon (Williams-Guillen et al. 2008; Nair et al. 2009; Jose 2009; Padmavathy and Poyyamoli 2011).

By integrating local indigenous trees and fruit varieties that are adapted to the local environment, the crops can be easily cultivated with few external input requirements. This leads to agroforestry-based integrated sustainable farming systems to alleviate poverty, to improve human nutrition, and to provide cash to farmers for facilitating sustainable livelihoods and livelihood diversification (Jaenicke et al. 2000; Ndoye et al. 2004; Schreckenberg et al. 2006; Nair 2011). Considering all such benefits of long-standing local practices of tree domestication in agroforestry practices by farmers, there is a recent shift in different parts of the world toward integrating indigenous tree species in general and fruit-bearing species with a potential to generate cash for farmers (Leakey and Simons 1997; Fentahun and Hager 2010).

6 Livelihood Security Through Agroforestry

Agroforestry research and development aim to reduce dependency on primary agricultural commodities and help to establish the production of added-value products based on raw agricultural materials. Smallholder tree production can make a significant contribution to improving rural livelihoods and strengthening national economies.

People depend on forests and trees in the developing countries in many ways (Dubois 2003):

- One-fourth of the world’s poor depend directly on forests for their livelihood.
- 350 million people live in or adjacent to dense forests and rely on them.
- At least 2 billion people rely on biomass fuels (mainly fuelwood) for cooking and heating.

- Forestry provides employment for more than 10 million people.
- Natural products from forests are the only source of medicine for 75–90% of people in the world.

Agroforestry is a viable option for ensuring livelihood security by its multiple services. This magnificent land-use technology offers an alternative solution to address low land productivity for resource-constrained smallholder farmers (Puri and Nair 2004). Agroforestry homegardens are primarily used for subsistence purposes by households; they are increasingly being used to generate income (Mendez et al. 2001). The quantity of agroforestry homegardens production that actually gets sold is highly variable, differing from one household to another.

7 Household Drivers of Forest Dependence for Employment

Direct employment is provided by the forest department and other line departments in the form of managerial, technical, research, planning, and executive jobs (Islam et al. 2013). Other direct employments consisted of labor force for rural masses generated by these departments under regular forestry activities are development and maintenance of forests, research and training, survey of forest resources, protection and conservation, soil and water conservation, felling, logging, conversion, transport and storage of timber, harvesting, collection and processing of non-timber forest products (NTFPs), preparation of nurseries, fencing, soil working, transplanting, planting, tending operations, watering, fertilizer and pesticide application, protection and management of plantation, and infrastructure development (Kumar 2009; Maske et al. 2011).

The self-employment in forestry creates local people's livelihoods through sale of fuel wood and fodder, grazing, lopping and grass cutting, forest-based handicrafts and cottage industries, sericulture, lac cultivation, bee keeping, charcoal burning, leaf plate making, liquor making, rope making and basketry, medicines, collection, processing and marketing of NTFPs, cultivation of agricultural crops under agroforestry, livestock rearing, social and farm forestry, and availing of rights and concessions (Sarmah and Arunachalam 2011; Shit and Pati 2012). The application of local skills and village-level technology provides secondary employment and livelihood opportunities, mainly among are saw milling, rayon, pulp and paper, plywood and panel products, wood seasoning and preservation, tanning, sports goods, match splints, veneers, wooden boxes, bamboo and cane products, agricultural implements, furniture, structural timbers, musical instruments, *bidi* (local cigarette)-making, educational goods, wood carving, wooden utensils, etc. (Singh and Quli 2011; Sharma et al. 2015). Forest development integrated with agricultural and industrial progress has great potential to enhance livelihood security, poverty reduction, and food security for vulnerable section of society in rural India (Tewari 2014; Shackleton and Pandey 2014).

8 Conclusion

An improved agroforestry system brings significant change in the agricultural farming systems among farming communities and affects farming households. Forests and trees support food security and nutrition in several ways. A wide range of trees outside forests including wild foods can be managed sustainably with diverse land-uses to secure easily accessible and essential micronutrient within the diet of rural population. There is massive scope in promotion and development of forest-based employments through proper storage and value addition to forest resources, their domestication and commercialization, organized marketing system, proper refinement and dissemination of indigenous technologies, training and skill development, and generating new avenues. Value addition can increase the financial returns from smallholder forestry and provide employment opportunities. Various measures can be implemented to encourage forestry value-adding activities. The promotion of agroforestry technologies is important because it offers the prospect of increasing production and hence raising farmers' income.

Sustainable development through agroforestry can be achieved through a concerted effort to actively and continuously encourage farmers' involvement in agroforestry activities. Agroforestry allows the growth of multiple crops simultaneously and provides several livelihood benefits to farming households. Commercial agroforestry is important for assured income as compared to traditional, but both forms of agroforestry have specific roles to play in the livelihoods. Agroforestry has positive impact on the asset base and livelihoods of poor households. Benefits may take long to make impact, but there is long-run profitability. Therefore, agroforestry is significant in improvement of rural community livelihoods.

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Chapter 35
Socioeconomic and Policy Considerations in the Adoption of Agroforestry Systems: An Ecosystem-based Adaptive Governance Approach

K. Akamani and E. J. Holzmueller

Abstract Owing to the shortfalls in conventional approaches to forestry and agriculture, agroforestry has been receiving attention among researchers and policymakers since the 1970s as an alternative land use strategy in tropical systems. Agroforestry is a promising strategy for deriving a range of benefits, such as food and water security, ecosystem health, energy security, and human health particularly in developing nations. Agroforestry is also posited as a means of producing various ecosystem services necessary for mitigation and adaptation to climate change impacts. In spite of these expected benefits, the adoption of agroforestry policies has been limited, and the potential contributions of agroforestry to resilience and sustainable development remain unrealized. Drawing from theoretical insights in ecosystem management and adaptive governance, this chapter discusses the potential benefits of managing agroforestry systems as complex adaptive social-ecological systems. Ecosystem-based adaptive governance holds promise as a framework for increasing the adoption of agroforestry as a land-use strategy for achieving sustainable development and social-ecological resilience by promoting a more inclusive and dynamic approach to developing locally-based agroforestry models. The modified taungya system in Ghana and other relevant case studies are used to illustrate the argument.

Keywords Adaptive governance · Adaptive management · Adoption · Ecosystem management · Resilience · Social-ecological systems · Sustainable development

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1 Introduction

Over the last half century, agroforestry has received increasing attention among academics and policy-makers. Since the 1970s, it has been seen as a land use strategy with the potential for addressing the shortfalls of modern forestry and agriculture, particularly in tropical systems (Sanchez 1995; Nair 1998). Mbow et al. (2014c) define agroforestry as “the body of knowledge and set of practices that explore and guide the integration of trees into crop, livestock and mixed agricultural systems at nested scales from a farmer’s field to large agricultural landscapes” (p. 162). Agroforestry holds the potential for reconciling the social, economic, and environmental dimensions of sustainable development by contributing to food security, poverty reduction, sustainable livelihoods, human health, and healthy ecosystems (Garrity 2004; Valdivia and Poulos 2009; Mbow et al. 2014c). Agroforestry is also gaining recognition as a strategy for reconciling climate change mitigation and adaptation policies (Mbow et al. 2014a; Lasco et al. 2016), as well as enhancing the resilience of households in developing nations (Luedeling et al. 2014; Mbow et al. 2014b). In view of these expected benefits, agroforestry has been posited as a key strategy in the attainment of global agendas, such as the Millennium Development Goals (Garrity 2004) and the Sustainable Development Goals (Mbow et al. 2014c). Although a lot has been learned about the benefits of agroforestry systems over the years, these benefits can only be realized if agroforestry innovations are adopted and maintained over time (Mercer 2004; Mbow et al. 2014b). Unfortunately, the adoption of agroforestry as a sustainable land use approach has been limited, and the potentials of agroforestry in enhancing resilience and sustainable development remain largely unrealized (Pattanayak et al. 2003; Mercer 2004). An urgent need exists for studies that explore the requirements for the adoption of agroforestry in order to inform policies that seek to provide enabling environments for the mainstreaming of agroforestry (Current et al. 2009; Udawatta and Godsey 2010). The objective of this chapter is to explore why adoption of agroforestry practices has been low and how two emerging resource regimes, ecosystem management and adaptive governance of social-ecological systems, could potentially increase the adoption of agroforestry practices worldwide. In the next section of the chapter, an overview of the literature on diffusion and adoption of innovations in agricultural and agroforestry systems will be provided. Next, the concepts of ecosystem management and adaptive governance will be discussed. The following section will discuss potential roles of ecosystem management and adaptive governance in enhancing the adoption of agroforestry systems. This will be followed by a discussion of the modified taungya system (MTS) in Ghana as a case study. The final section shall contain concluding remarks.

2 Barriers to Adoption of Agroforestry

Beginning with sociological studies on the adoption of hybrid corn in the USA in the 1940s by Ryan and Gross (1943), a large body of literature has accumulated on the factors influencing the diffusion and adoption of innovations in agriculture, forestry, and agroforestry systems (Fliegel and Korsching 2001; Napier 2001; Rogers 2003; Pannell et al. 2006; Baumgart-Getz et al. 2012). Early research on diffusion and adoption of agricultural technologies focused on the communication of information on agricultural innovations to create awareness among farmers, as well as exploring the social-psychological determinants of farmers' interest in the voluntary adoption of innovations (Galjart 1971; Fliegel and Korsching 2001). Among the assumptions in this era of diffusion and adoption research are that technological innovations were inherently beneficial to the farmer and the larger society (Adesina and Zinnah 1993; Fliegel and Korsching 2001) and that farmers will adopt innovations when they are provided with information on the benefits of these innovations (Adesina and Zinnah 1993; Napier 2001). However, the application of these ideas in the developing world revealed that the focus on creating awareness and interest in innovations among farmers overlooked the larger social processes that influenced farmers' ability to adopt innovations (Galjart 1971).

Subsequent research on diffusion and adoption of innovations has since broadened its traditional micro level of analysis to account for the structural forces that influence the unequal access to the socioeconomic resources for adoption (Fliegel and Korsching 2001; Napier 2001). Also, in view of the adverse consequences from past production-oriented technological innovations in agriculture in tropical systems, assumptions about the inherent benefits of innovations are giving way to a more careful scrutiny of farmers' perceptions on the appropriateness of the attributes of innovations and how they influence the adoption process (Adesina and Zinnah 1993). These insights from the broader literature on the diffusion and adoption of innovations reflect findings on adoption in the agroforestry literature. In their review of the literature, Pattanayak et al. (2003) and Mercer (2004) identified five main factors influencing the adoption of agroforestry innovations. They comprise the preferences of the adopters, the resource endowments of the adopters, the availability of market incentives, the biophysical attributes of the land, and risk and uncertainties associated with adopting the innovation, such as price fluctuations and tenure insecurity. The review by Pattanayak et al. (2003) revealed that whereas the preferences and resource endowments of adopters were the most common variables included in adoption studies, it was risk and uncertainty, biophysical conditions, and the resource endowments of adopters that often significantly predict adoption behavior. Based on these insights, the adoption of innovations may best be conceptualized as an ongoing learning process, influenced by a broad range of sociocultural, economic, ecological, institutional, and technological factors across the micro-, meso-, and macro-levels that shape farmers' awareness, interest, and capacity for adoption (Pannell et al. 2006; Atwell et al. 2009; Valdivia and Poulos 2009; Prokopy et al. 2008; Reimer and Prokopy 2014).

Constraints in the adoption of agroforestry and other innovations have also received attention in the literature. Closely related to the issues discussed above, the constraining factors to adoption behavior include the lack of awareness of the innovation, lack of interest in adopting the innovation, and lack of capacity to adopt the innovation on the part of farmers (Galjart 1971; Pannell 1999; Place and Prudencio 2006; Akamani et al. 2015). Existing knowledge gaps include the need for innovative policy and institutional frameworks for overcoming the barriers and creating favorable conditions for adoption (Nair 1998; Garrity 2004; Current et al. 2009), as well as addressing the complex multilevel social and ecological drivers that influence the adoption process (Atwell et al. 2009). However, the institutional requirements for realizing the potentials of agroforestry have not been adequately explored (Nair 1998). In this chapter, we highlight the potentials of ecosystem management and adaptive governance of social-ecological systems as frameworks for increasing the adoption of agroforestry practices. Whereas the classical approach to diffusion views the process as a linear, rational, and centrally planned change process (Fliegel and Korsching 2001), the use of these alternative institutional frameworks offers a more inclusive and dynamic approach to fully developing locally based agroforestry models.

3 Ecosystem Management and Adaptive Governance

Conventional approaches to managing forests and water resources have fundamentally assumed social and ecological systems are distinct from each other and that natural ecosystem dynamics are predictable and controllable (Holling and Meffe 1996; Cortner and Moote 1999; Folke et al. 2002; Armitage et al. 2009). This resource management paradigm also entailed the overreliance on reductionist science and top-down decision-making mechanisms aimed at maximizing economic benefits from selected components of ecosystems through sustained yield management (Nelson et al. 2008; Folke et al. 2009; Chapin et al. 2010; Akamani et al. 2016). The shortfalls associated with this paradigm of resource management have led to the turn toward ecosystem management (Grumbine 1994; Cortner and Moote 1999; Chapin et al. 2009; Folke et al. 2011; Behnken et al. 2016).

The emergence of ecosystem management as an alternative to the conventional resource management paradigm is informed by a shift in thinking about the dynamics of ecosystems and the relationships between humans and nature. Ecosystem management is underpinned by complexity and resilience thinking (Thomas 1996; Yaffee 1996; Endter-Wada et al. 1998; Chapin et al. 2010). From this new perspective, social and ecological systems are assumed to be coupled with each other in a dynamic and eco-evolutionary fashion as inseparable social-ecological systems (Olsson and Folke 2001; Chapin et al. 2009; Folke et al. 2011). Unlike traditional assumptions of stability and predictability of ecosystems that informed past resource management approaches (Hughes et al. 2005; Folke 2006; Berkes 2007), complex social-ecological systems, such as agroforestry systems, are assumed to exhibit the attributes of complex adaptive systems, such as surprise, nonlinearity, emergence, scale sensitivity, and path dependency (Folke 2007; Liu et al. 2007; Folke et al. 2011; Akamani et al. 2016).

Based on these assumptions, ecosystem management is ultimately about building the resilience of social-ecological systems (Loomis 2002). Social-ecological resilience refers to the amount of disturbance a system can absorb while maintaining its structure and function, the degree to which a system is capable of self-organization, and the ability to learn and adapt to change (Carpenter et al. 2001; Folke et al. 2002; Folke 2006). Thus, resilient social-ecological systems have the capacity to adapt or transform in response to drivers of change (Redman 2014; Folke et al. 2010, 2016). Consistent with this goal, ecosystem-based resource management adopts a holistic approach that emphasizes the integrated management of land and water resources to achieve long-term social, economic, and ecological sustainability (Thomas 1996; Endter-Wada et al. 1998; Folke et al. 2011). Another defining attribute of ecosystem management is its bioregional scale, which emphasizes resource management at multiple spatial and temporal scales (Cortner et al. 1998; Lee 1999; Olsson and Folke 2001). Moreover, ecosystem management also departs from the dominance of disciplinary experts by prioritizing the use of diverse sources of knowledge through various forms of disciplinary collaboration, as well as recognition of local and traditional knowledge (Endter-Wada et al. 1998; Cortner and Moote 1999; Olsson and Folke 2001).

An integral part of ecosystem-based resource management processes is the use of adaptive management as a means of dealing with uncertainties (Lee 1999; Butler and Koontz 2005; Keough and Blahna 2005). The concept of adaptive management (Holling 1978; Walters 1986) is based on the recognition of the inherent uncertainty and unpredictability of complex social-ecological systems. Adaptive management provides a framework for dealing with these uncertainties by promoting learning (Gunderson 1999; Allen and Gunderson 2011; Williams 2011). In active adaptive management, resource management policies are explicitly treated as hypotheses that are subsequently tested through management experiments to probe ecosystem responses (Lee 1999; Gunderson and Light 2006; Walters 2007). However, adaptive management may also take the form of evolutionary adaptive management where learning occurs in an unguided manner through trial and error or passive adaptive management where policies informed by historical experience are implemented and monitored over time (Allan and Curtis 2005). While adaptive management processes hold promise as mechanisms for managing uncertainty, success in adaptive ecosystem-based management processes calls for appropriate institutional mechanisms for addressing the social complexity entailed in such processes (Gunderson and light 2006; Allen et al. 2011; Walker 2012).

With regard to institutions, an appropriate institutional framework for pursuing ecosystem-based resource management is adaptive governance (Folke et al. 2005; Schultz et al. 2015; Valman et al. 2015). Adaptive governance is informed by theoretical insights from the literature on resilience and adaptive management of social-ecological systems and the governance of common pool resources (Nelson et al. 2008). These theoretical insights highlight the need for effective governance systems for managing complexity and uncertainty, as well as conflicting values and interests in order to ensure sustainable human-environment relationships (Dietz et al. 2003). Adaptive governance refers to institutional mechanisms that connect individuals and organizations across multiple levels to provide a flexible, learning approach to ecosystem management (Olsson et al. 2006; Schultz et al. 2015). Dietz et al. (2003) identified the key requirements of adaptive governance to comprise provision of trustworthy information, managing conflicts, ensuring rule compliance, provision of infrastructure, and preparing for change. The authors further identified three strategies for meeting these requirements: analytic deliberation, nesting, and institutional variety.

First, adaptive governance systems rely on analytic deliberation processes that engage scientists, resource managers, and other stakeholders in structured decision-making processes (Dietz et al. 2003). Nelson et al. (2008) note that technical analysis of scientific information alone is inadequate in addressing the value conflicts and trade-offs in the management of common pool resources. As an alternative, analytic deliberation combines public deliberation with scientific analysis to address scientific uncertainty and value conflicts (Dietz and Stern 1998; Dietz 2013). A second strategy for adaptive governance is the nesting of institutions across multiple levels (Dietz et al. 2003). Complex social-ecological systems are hierarchically nested with shared attributes as well as unique features across the various levels. Relying on uniform policy prescriptions from top-down institutions has the potential to create mismatches or lack of fit between policy prescriptions and the scales of intervention (Cash et al. 2006; Folke et al. 2007). The nested institutional structure of adaptive governance provides a mechanism for enhancing the fit between problems and institutional interventions (Olsson et al. 2007; Olsson and Galaz 2009; Akamani and Wilson 2011). While such nested polycentric institutions may sometimes be considered inefficient, they provide opportunities for experimentation at lower levels and may also provide buffers in the event of failure at a given level (Chapin et al. 2010; Folke et al. 2011). Finally, adaptive governance relies on a variety of institutions to provide a range of incentives for ensuring rule compliance (Dietz et al. 2003). Through this attribute of diversity, adaptive governance systems combine the benefits of centralized, community-based, and market-based solutions, thereby enhancing the overall effectiveness of the system (Nelson et al. 2008; Akamani and Wilson 2011). In all, adaptive governance provides an effective mechanism for enhancing multilevel collaboration, promoting adaptive management, managing conflicts, and building the capacity for social-ecological transformation (Gunderson and Light 2006; Olsson et al. 2006; Folke et al. 2009; Walker 2012). The ecosystem-based adaptive governance approach holds promise as a mechanism for overcoming the challenges in the transition toward the widespread adoption of agroforestry policies and practices. However, these potentials remain largely unexplored in research and policies on agroforestry systems.

4 Ecosystem-based Adaptive Governance of Agroforestry Systems

This section elaborates on the major challenges in the adoption and diffusion of agroforestry systems and discusses how policies based on the principles of ecosystem management and adaptive governance could potentially contribute to overcoming these challenges. The discussion is informed by relevant examples from various geographic regions, particularly Africa and Latin America. The scope of the discussion covers multiple levels of analysis, ranging from farmer and farm level considerations to policy considerations at the landscape level.

4.1 Creating Awareness About Agroforestry Innovations

A key condition in the adoption of agroforestry practices is farmers' awareness of agroforestry innovations and their potential benefits (Pannell 1999). Yet the level of awareness about the potential benefits of agroforestry is inadequate (Garrity 2006), and policy-level recognition of agroforestry remains limited in developing nations (Rudebjer et al. 2006; Mbow et al. 2014b). The fragmentation and isolation of disciplines, as well as neglect of the human dimensions in early agroforestry research, have impeded the holistic understanding of social-ecological interactions in agroforestry systems (Parker & Burch 1992). Also, due to the overemphasis of early agroforestry research on biophysical issues at fine scales (Nair 1998), the long-term benefits of agroforestry at larger scales are poorly understood (Udawatta and Godsey 2010). When information is available, extension and education systems for disseminating information on agroforestry have yielded mixed results, further complicating the issue (Rudebjer et al. 2006). One of the primary reasons may be attributed to the overemphasis on disseminating scientific knowledge generated from public sector institutions, such as agricultural experiment stations, with little appreciation of local and indigenous knowledge (Fliegel and Korsching 2001; Rosset and Martinez-Torres 2012). This style of dissemination is embedded in a broader, top-down development model, which assumes local farmers are ignorant, backward, and therefore less developed (Altieri 2002, 2009; Altieri and Nicholls 2012). Critical steps toward enhancing the adoption of agroforestry policies therefore include providing farmers, policy-makers, and other stakeholders with science-based evidence on agroforestry benefits and barriers, as well as trade-offs and synergies, and enhancing access to such information (Garrity 2004; Lasco et al. 2014; Mbow et al. 2014b).

Agroforestry policies informed by ecosystem management and adaptive governance principles could potentially enhance the gathering and dissemination of reliable information to create awareness among stakeholders in agroforestry. Adaptive governance emphasizes the need for enhanced access to accurate and reliable policy-relevant information on human-environment interactions (Dietz et al. 2003; Pahl-Wostl et al. 2012; Akamani 2016). Gaining a holistic understanding of complex social-ecological systems, such as agroforestry systems, requires the integration of knowledge from different perspectives and levels of scale since no single type of knowledge or level of observation will be adequate in understanding the complexity (Berkes 2004; Armitage et al. 2012; Akamani et al. 2016). This calls for multidisciplinary, interdisciplinary, and transdisciplinary collaboration among researchers from diverse academic backgrounds in agroforestry research (Izac and Sanchez 2001; Smith and Mbow 2014; Sereke et al. 2016). Such knowledge integration will require enhanced recognition of the social sciences in agroforestry science and policy (Burch 1992; Burch and Parker 1992; Nair 1998). In DPR Korea, for instance, economic crisis in the early 1990s triggered by the collapse of the Soviet Union resulted in massive deforestation as people harvested timber for fuel and cultivated sloping lands for food. As a response, a bottom-up participatory agroforestry approach was adopted in the implementation of the sloping land management (SLM) project that aimed at halting deforestation, increasing food production, and generating income from hills and mountains. Xu et al. (2012) partly attribute the success in the implementation of SLM project to the role of a multidisciplinary research team facilitated by the Ministry of Land and Environmental Protection, as well as other partner organizations and universities.

Unlike conventional top-down approaches to extension which marginalize local knowledge (Altieri 2002), an ecosystem-based adaptive governance approach to agroforestry also supports the greater recognition and utilization of the knowledge local communities have accumulated over time through traditional agroforestry practices. This is consistent with ongoing calls for respect for local ecological knowledge in agroforestry research (Sanchez 1995; Smith and Mbow 2014). In Niger, rapid deforestation between the 1950s and 1980s further exposed the country to threats of desertification and the adverse impacts of drought, high temperatures, strong winds, and infertile soils (Rinaudo 2007; Tougiani et al. 2009). These environmental pressures combined with socioeconomic challenges, such as poverty and high population growth, increase the incidence of hunger and famine (Rinaudo 2007). For decades, efforts to promote reforestation and reduce desertification relied on conventional forestry methods that entailed raising and planting exotic tree species. However, this approach yielded little success due to the harsh environmental and socioeconomic conditions in the region. Beginning in the 1980s, an alternative to the conventional methods of reforestation, known as the Farmer-Managed Natural Regeneration (FMNR) method, was developed and disseminated by researchers from World Vision Australia. Rather than planting new trees, this innovation focuses on the regeneration of the abundant tree stumps of indigenous tree species in the region as a means of restoring croplands, grazing lands and degraded communal forests (Rinaudo 2007; Haglund et al. 2011). Since its introduction, this innovation has spread across the Sahel, as well as other regions including northern Ghana (Weston et al. 2015). Benefits accruing from the FMNR method include poverty reduction, enhanced food security, environmental sustainability, enhanced community resilience to climate change impacts, and contributions to climate change mitigation (Rinaudo 2007; Tougiani et al. 2009; Haglund et al. 2011; Weston et al. 2015). In Niger in particular, FMNR has been implemented on over 5 million hectares of farmland, on which about 200 million trees have been planted (Sendzimir et al. 2011). Participating farmers are estimated to be earning an additional USD$ 200 per household per year and producing an estimated additional 500,000 tons of cereal a year which covers the food requirements for some 2.5 million people (WVI 2012). Tougiani et al. (2009) describe the harnessing of local ecological knowledge as an integral part of the successful reforestation efforts in the FMNR program. These findings are consistent with the benefits of local ecological knowledge that have been extensively discussed in the field of agroecology (Rosset and Altieri 1997; Altieri 2002; Altieri and Nicholls 2012; Rosset and Martinez-Torres 2012).

Regarding knowledge dissemination, conventional approaches to extension whereby farmers are treated as passive recipients of expert knowledge (Fliegel and Korsching 2001) have been critiqued for its disempowerment of farmers and failure to promote widespread adoption (Rosset and Martinez-Torres 2012). As an alternative, the concept of social learning, which refers to learning that occurs at the collective level through social interactions within actor networks (Reed et al. 2010), is being acknowledged as a more effective means of enhancing awareness about agricultural and agroforestry innovations than conventional outreach mechanisms (Pretty and Hine 2001; Smith and Mbow 2014). Promoting social learning and knowledge coproduction among diverse stakeholders requires institutional mechanisms that enable meaningful and sustained social interaction processes (Armitage et al. 2011; Measham 2013). The nested institutional structure and the analytic deliberation processes of adaptive governance provide opportunities for sustained interactions among stakeholders through which the integration of different types of knowledge among the diverse participants, as well as social learning, could occur (Akamani and Wilson 2011; Dietz 2013). Using adaptive governance to promote social learning calls for the use of participatory action research (Aytur et al. 2015; Akamani 2016), whereby scientists and other stakeholders interact as equal partners throughout the various stages of the research process (Pretty 1994; Fortmann 2008). A widely publicized success story is the Campesino-a-Campesino (CAC), i.e., farmer-to-farmer or peasant-to-peasant method for developing and spreading agroecological innovations among small-scale farmers that was developed in Guatemala in the 1970s and has since spread to other parts of Latin America (Rosset and Martinez-Torres 2012). Consistent with its participatory approach, the CAC harnesses the capacity of farmers to solve their own problems by drawing from their local knowledge, resources, and historical experience. Knowledge is collectively constructed and horizontally transmitted from farmer to farmer to solve their common problems. In Cuba, within a decade of the introduction of CAC by the National Association of Small Farmers as a means of disseminating information on agroecology and promoting its adoption by farmers, the program has been adopted by more than 110,000 farmers representing one-third of all peasant families, thus resulting in a transformation of Cuba's agricultural landscape toward integrated and diversified farming systems. Benefits associated with this transition include enhanced innovativeness of farmers through integration of traditional peasant knowledge with the science of agroecology; enhanced farm productivity, food security, and sovereignty;

and enhanced resilience to climate change impacts (Rosset et al. 2011; Altieri and Nicholls 2012; Rosset and Martinez-Torres 2012).

Conventional approaches to analyzing diffusion of conservation practices are underpinned by linear, predictable conceptualizations of the adoption process (Fliegel and Korsching 2001). However, given the complexity of agroforestry systems, innovations that provide opportunities for trial could be critical for enhancing adoption by managing uncertainties and reducing the risk-averse nature of farmers (Pannell 1999; Pannell et al. 2006). As has been previously discussed, a central component of ecosystem-based adaptive governance is adaptive management which treats the resource management process as a means of learning to deal with change and uncertainty (Walker 2012). Agroforestry policies based on principles of ecosystem-based adaptive governance could provide opportunities for experimentation and learning through adaptive management. For instance, the implementation mechanisms of the FMNR program in Niger contained flexible mechanisms that allowed farmers to meet the needs on their farms by experimenting and adapting to the changing climatic conditions (Tougiani et al. 2009). Similarly, the implementation of CAC in Cuba has an adaptive component to it that promotes a learning-by-doing approach among farmers. The underpinning idea is that where farmers have an opportunity to observe how well a particular technique is performing on the farms of their peers, they're more likely to be convinced than when the technique is simply recommended by an external expert (Rosset et al. 2011; Rosset and Martinez-Torres 2012). This adaptive farmer-to-farmer approach provides opportunities for farmers to be involved in the trailing and monitoring of the performance of technologies prior to making adoption decisions.

4.2 Cultivating Interest in Agroforestry

Farmers' adoption of agroforestry practices ultimately depends on perceptions of the potential of agroforestry to promote their self-interest, defined broadly to include economic and noneconomic considerations (Pannell 1999; Pannell et al. 2006). As Mercer (2004) has succinctly stated, "farmers will invest in agroforestry when the expected gains from the new system are higher than the alternatives for the use of their land, labor and capital". The factors influencing farmers' interest in the adoption of agroforestry practices occur at multiple levels and domains, such as individual and household characteristics, attitudes and preferences, biophysical factors, as well as access to markets and incentives (Valdivia and Poulos 2009).

Agroforestry policies pursuing integrated goals that take into account the needs of local communities, such as sustainable livelihoods, are more likely to provide the incentives needed to generate farmers' interest in agroforestry adoption (Mbow et al. 2014c). The livelihood concept represents a broader conception of employment (Chambers 1995). Livelihoods encompass all the strategies employed by individuals and their households to make a living based on their capabilities and access to capital assets, such as human capital, natural capital, social capital, physical capital, and financial capital (Scoones 1998; Plummer and Armitage 2007). Livelihoods are sustainable when they can cope with and recover from stresses and shocks while maintaining or enhancing their capabilities and assets (Scoones 1998; Rakodi 1999). Agroforestry policies based on the holistic orientation of ecosystem-based management could contribute to promoting sustainable livelihoods. Ecosystem management adopts an integrated approach to pursuing social, ecological, and economic goals aimed at enhancing sustainability (Folke et al. 2011). In Niger, for instance, early adopters of the FMNR program were faced with unfavorable community attitudes, including ridicule and theft of their trees (Rinaudo 2007). However, the design and implementation of the FMNR program prioritized tangible benefits to farmers starting from the first year of the program, including food, firewood, fodder, and windbreaks (Tougiani et al. 2009; Kates et al. 2012). Following awareness creation about the FMNR program, the implementation of a "Food for Work" program in 95 villages provided incentives that attracted farmers to adopt the program. Participants who benefitted from this phase of the program helped in spreading the innovation from farmer to farmer through word of mouth (Rinaudo 2007). Changes in national forestry laws in Niger also created incentive packages, such as granting ownership of trees or tree user rights to the farmers who were leading the reforestation process. Prior to the policy change, farmers had no incentive to protect trees under the old laws that granted no tree ownership rights and responsibilities to local communities.

A key challenge in such an integrated approach to agroforestry is how to manage the synergies and trade-offs among the multiple interests across multiple scales (Smith and Mbow 2014). Adaptive governance provides opportunities for political solutions to such wicked problems rather than sole reliance on technical solutions (Nelson et al. 2008; Akamani et al. 2016). The analytic deliberation process of adaptive governance provides negotiated solutions to value trade-offs by engaging all stakeholders in a conflict management process that combines scientific analysis with public participation (Dietz and Stern 1998; Dietz 2013). This integration of scientific analysis with stakeholder interaction and deliberation provides a more promising approach to identifying and managing the synergies and trade-offs among the multiple values that exert demands on agroforestry across multiple scales. For instance, Ashby et al. (1996) describe the application of participatory research methods in involving farmers in the design of soil conservation practices in the Rio Ovejas watershed in Colombia. The result was a dramatic increase in adoption among participant farmers, as well as an increase in spontaneous adoption among nonparticipants through farmer-to-farmer recommendations. The enhanced adoption rates were achieved because the process recognized farmers' criteria for choosing among alternative conservation strategies – criteria which often resulted in choices different from those recommended by scientists. The authors highlighted the need for devising methods to achieve trade-offs between utilitarian and conservation values that are acceptable to farmers in order to enhance adoption rates.

Besides economic incentives, noneconomic considerations, such as social capital, are equally important in shaping farmers' interest in the adoption of agricultural and agroforestry technologies (Pretty and Hine 2001; Altieri 2002). Social capital refers to the social norms, as well as relationships of trust and reciprocity that promote cooperative behavior and collective action (Fukuyama 2001; Pretty 2003). Institutional arrangements that promote repeated face-to-face interactions among participants can serve as an arena for the accumulation of social capital for collective action (Ostrom 1990). While the strong reliance on top-down institutions in the implementation of agroforestry projects has led to social conflicts (King 1987), the analytic deliberation process and nested institutional structure of adaptive governance could provide opportunities for vertical and horizontal communication and interaction among stakeholders through which trust and social capital could develop (Dietz et al. 2003; Armitage et al. 2009) to promote the adoption of agroforestry policies and practices at the collective and individual/household levels. For instance, Marshall (2009) analyzed farmers' adoption of conservation practices under community-based governance regimes in Australia and concluded that polycentric institutional structures play an essential role in providing opportunities for sustained interactions at the local level through which norms of reciprocity and cooperative behavior emerge among farmers to promote the voluntary adoption of conservation practices.

4.3 Building Capacity for Adoption

The trialing and adoption of agroforestry technologies entail significant resource requirements (Pannell 1999). Farmers and other technology adopters must have these required resources, such as land, labor, and financial capital, in order to adopt innovations (Pattanayak et al. 2003). Adoption of agroforestry innovations may be hindered by the complexity of agroforestry systems as well as the longer time it takes to realize benefits compared to conventional agriculture (Mercer 2004). Studies show that "early adopters tend to be the better-off households who are better situated to take advantage of new innovations with uncertain prospects" (Mercer 2004: 323). Better-off families could be willing to invest in agroforestry innovations simply because they have the means to do so. Even if poorer households are interested in innovations, they do not have the surplus resources that will enable them to take risks. Thus, the widespread poverty and inequality in most rural communities in the developing world present serious challenges to the equitable and successful implementation of agroforestry programs.

An ecosystem-based adaptive governance approach to agroforestry systems has the potential to build capacities of actors across scales. The nested institutional structure of adaptive governance operates based on the principle of subsidiarity, whereby decision-making responsibilities are located at the lowest appropriate level of the institutional hierarchy (Marshall 2008). This could create opportunities for strengthening the role of local institutions in the formulation and implementation of policies, such as those on agroforestry (Akamani et al. 2015). In Niger, the success of the FMNR program was enhanced by policy changes by the Nigerien government made possible through negotiations involving a range of actors, including

US Agency for International Development (USAID). These institutional reforms granted local communities the authority to devise and enforce local rules to protect their property (Rinaudo 2007), thus contributing to local empowerment.

Access to information and other critical resources could also be enhanced through the vertical and horizontal linkages among participants within the nested institutional framework of adaptive governance (Akamani and Wilson 2011). The pooling of resources within networks from the local to the global has been noted as a critical strategy for capacity building in agroforestry systems (Njuki et al. 2006). Again in Niger, training and capacity-building efforts that contributed to the success of the FMNR program came through the coordinated efforts of a network of national and international organizations, as well as church groups who contributed to spreading the innovation across Niger (Rinaudo 2007; Sendzimir et al. 2011). Other factors that accounted for the success of the program include its relatively low cost, local leadership in the implementation process, and reliance on local skills and resources that reduced the resource requirements of the program. Similarly, the success of CAC in the transition toward agroecology in Cuba and other Latin American countries was facilitated by the efforts of governmental and nongovernmental organizations across multiple levels that contributed to the emergence of a social movement of peasant farmers advocating for policy change toward agroecology (Altieri and Toledo 2011; Altieri and Nicholls 2012; Rosset and Martinez-Torres 2012).

Finally, capacity building in agroforestry could also be enhanced through the analytic deliberation processes of adaptive governance that provides a mechanism for managing conflicting values among stakeholders. This emphasis on conflict management is essential in addressing the interests of traditionally marginalized groups, thereby enhancing equity in agroforestry processes and outcomes. Given concerns over the potential for the process of diffusion and adoption of innovations to widen existing socioeconomic gaps (Fliegel and Korsching 2001; Altieri 2002), the potential for ecosystem-based adaptive governance to enhance equity in agroforestry systems is particularly important. For instance, in their analysis of the relationship between natural resource conflicts and the adoption of agroforestry technologies in Uganda, Sanginga et al. (2007) found positive relationships between certain types of conflicts and the adoption of agroforestry technologies. The authors concluded that conflicts can be converted into opportunities for adoption where institutional mechanisms exist to promote social capital and conflict management.

5 Case Study: The Modified Taungya System in Ghana

The taungya system, which originated from Burma in the latter part of the nineteenth century (King 1987), is the type of agroforestry practiced in Ghana. According to Menzies (1988), “Taungya is a system of forest management in which land is cleared and planted initially to food crops. Seedlings of desirable tree species are then planted on the same plot, leading in time to a harvestable stand of timber.” There exists a lack of consensus on the inception of modern agroforestry in Ghana.

Agyeman et al. (2003) trace the origins of Ghana's agroforestry initiative to the 1930s, whereas Blay et al. (2008) trace it to the 1960s. Ghana's taungya system was introduced with the goal of enhancing the production of commercial timber while addressing the need for farmlands for food crop production in forest-dependent communities (Agyeman et al. 2003). The program involved the allocation of land in degraded forests to farmers who would grow food crops while helping in forest restoration efforts by establishing and maintaining trees. Food crop cultivation normally continued for 3 years, after which farmers were expected to vacate their plots and move to other plots when the tree canopy closes. In an era when forest decision-making and implementation in Ghana followed a top-down, nonparticipatory approach, the taungya system served as an important link between communities and the Ghana Forestry Commission (Mayers and Kotey 1996). However, the program was suspended in the 1980s due to a broad range of factors that accounted for its widespread failure, including lack of equity in benefit sharing, lack of involvement of farmers in decision-making processes, and lack of tree ownership rights by farmers (Blay et al. 2008; Kalame et al. 2011). Mayers and Kotey (1996) have identified that the most critical factors that determined the success or failure of the taungya system across communities were the level of farmers' interest in the program and the availability of community organizational or institutional capacity to manage the program.

The program was reintroduced as the modified taungya system (MTS) in the early 2000s by the Government of Ghana with support from the World Bank and the Food and Agriculture Organization (Agyeman et al. 2003). The MTS program operates within an enabling policy environment created by the Forest and Wildlife Policy of 1994 that is aimed at collaborative forest management, sustainable forestry, and the equitable sharing of forest benefits among the various stakeholders, including farmers, communities, and the Ghana Forestry Commission (Akamani and Hall 2015). Consistent with this new policy environment that promotes collaborative forest management, the MTS program contains mechanisms for the sharing of benefits and responsibilities among the various stakeholders in the plantation development process (Ros-Tonen et al. 2013). With regard to responsibilities, the Ghana Forestry Commission is expected to provide technical expertise, training, and extension services. The agency is also responsible for the provision of farm inputs, such as seeds and equipment, assisting farmers with marketing, and providing financial support for farmers. Land-owning authorities are responsible for providing land for the plantation establishment. Farmers are required to provide labor or bear the cost of plantation establishment and protection against wildfire. Finally, communities are also expected to provide labor for protecting the plantation from wildfire and illegal activities, such as logging. In terms of benefits, farmers are entitled to 100% of benefits from food crop production during the first 4 years of plantation establishment until tree canopy closure. However, farmers are expected to continue to maintain the plantation until the trees reach maturity, at which point farmers and the Ghana Forestry Commission each are entitled to 40% of timber benefits, land owners are entitled to 15%, and communities are entitled to 5% (Agyeman et al. 2003; GFC 2016).

The MTS program was implemented as a component of the National Forest Plantation Development Program (NFPDP) that was launched in 2001 to achieve various goals, including forest restoration, provision of industrial timber, generation of employment, enhancement of food production, and protection of environmental quality (GFC 2016). A recent annual report by the Ghana Forestry Commission indicates that 185,527 ha of degraded forest were restored under the NFPDP between 2001 and 2015 (GFC 2016). However, the implementation of the MTS program was suspended in 2009. Between 2002 and 2009, an estimated 80,727 ha of degraded forests were restored under the MTS program (GFC 2014). Based on insights from ecosystem management and adaptive governance discussed earlier, a number of potential shortfalls can be identified in the MTS program in the areas of awareness creation, provision of incentives, and capacity building that helps explain the suspension of the program.

First, the mechanisms for generating and sharing information on the MTS program appeared to follow the conventional model, whereby knowledge is generated by expert scientists and transmitted to farmers who are expected to modify their practices in response to the new knowledge. As such, mechanisms for promoting knowledge integration, social learning, and adaptive management were not adequately integrated into the MTS program. In their analysis of the MTS program, Ros-Tonen et al. (2014) noted that decisions such as the selection of tree species and food crops, as well as how planting should be done, were all made by the Ghana Forestry Commission based on their field trials without the direct input of participating farmers. Such expert-driven approaches that do not adequately integrate the local knowledge of farmers hinder the acceptability of program prescriptions. For instance, studies have shown that while fast-growing exotic tree species, particularly *Tectona grandis* (teak) and *Cedrela odorata* (cedrela), were the dominant species farmers were advised to plant in the MTS program (Ros-Tonen et al. 2013), some farmers expressed preference for indigenous tree species (Akamani 2011; Acheampong et al. 2016). Similarly, researchers have reported farmers' widespread dissatisfaction over the ban on planting of the cassava crop in the MTS program by the Ghana Forestry Commission, as cassava is a staple food in the region where the program is being implemented (Ros-Tonen et al. 2013; Acheampong et al. 2016).

Second, constraints can also be found in the provision of incentives in the MTS program. With regard to economic benefits, farmers and staff of the Ghana Forestry Commission agree on the notion that the current benefit-sharing agreement puts enormous financial burden on farmers (Akamani et al. 2015). Although farmers gained short-term benefits in terms of food supply and income in the first 3 years of the program, they were required to take care of the trees till they mature before substantial income from timber sales can be realized. In this regard, the Ghana Forestry Commission identified farmers' inability to undertake the maintenance of the plantations as one of the major constraints to the program (GFC 2014). Moreover, participating farmers have expressed a lack of certainty in these future benefits due to the long time it takes, as well as the absence of legal contractual agreements on the benefit-sharing scheme (Akamani et al. 2015; Acheampong et al. 2016). A report by the Ghana Forestry Commission states that only 296 out of an estimated 2000 forest-dependent communities have signed the legally binding benefit-sharing agreement on the MTS program (GFC 2014). Beside these economic issues, the incidence of conflicts arising out of competition among participants and lack of transparency in forest land allocation in the MTS program also hindered the development of social capital for cooperative action among participating farmers and other forest user groups (Derkyi et al. 2014; Akamani et al. 2015).

Finally, shortfalls can also be found in the mechanisms for community capacity building in the MTS program. In the early days of the collaborative forest management program, the Ghana Forestry Commission initiated a program to build the capacity of forest-dependent communities through the establishment of community-based forest organizations, known as Community Forest Committees (CFCs). The CFCs were expected to play an essential role by serving as a link between forest-dependent communities and external organizations in the implementation of collaborative forest management projects, such as the MTS program. However, this initiative on community institutional capacity building did not receive adequate and sustained support from the relevant governmental and nongovernmental organizations (Akamani 2011, Akamani et al. 2015). Similarly, the establishment of Land Allocation and Tangya Management Committees (taungya committees) to facilitate the implementation of the MTS program at the community level has reportedly not received enough support from the Ghana Forestry Commission (Acheampong et al. 2016). A report by the Ghana Forestry Commission identified the absence of reliable funding and equipment as constraints to plantation establishment, maintenance, and monitoring efforts (GFC 2014). Besides these institutional constraints, the inadequacy of socioeconomic resources, such as access to credit, farm inputs, as well as transportation and marketing services, has also impeded the capacity of households to benefit from the MTS program (Akamani 2011; Akamani et al. 2015).

6 Conclusions

Since the 1970s, the potential of agroforestry as a land use strategy for achieving various social, ecological, and economic goals has been receiving attention, but this has not been the case in policy and practice. The constraints appear to be rooted in the absence of institutional mechanisms for providing the information, incentives, resources, and opportunities for the transition from existing conventional policies and practices in forestry and agriculture toward agroforestry. As a consequence, the potentials of agroforestry remain largely unrealized. In order to increase the adoption of agroforestry practices, an ecosystem-based adaptive governance approach to agroforestry system is necessary. This approach holds promise for overcoming the barriers to agroforestry adoption as well as managing the complexity and uncertainties that characterize agroforestry systems.

The application of these theoretical insights to the implementation of agroforestry policies in Ghana has shown that the collaborative nature and benefit-sharing attributes of the MTS program represent an improvement over previous policies that relied on top-down decision-making procedures without adequate benefits for communities. However, failure to integrate diverse sources of knowledge, inadequacy of benefits to farmers, and inadequacy of community capacity building may have contributed to the demise of the MTS program. Addressing the shortfalls of the MTS program through ecosystem-based adaptive governance principles will require a number of measures, including taking complexity and adaptive management seriously, complementing expert scientific knowledge with local knowledge through participatory social learning processes, promoting integrated goals that address the livelihood security of local communities, and using diverse, multilevel institutions that include strong formal and informal institutions at the local level.

While the chapter has highlighted the benefits of such a transition, it must also be noted that there is little evidence and understanding on social-ecological transitions toward ecosystem-based resource management and adaptive governance (Folke et al. 2009). The difficulty of orchestrating deliberate transformation at large scales (Folke et al. 2011), the risks and uncertainties entailed in the change process (Chapin et al. 2010), and the inadequacy of methodological protocols for assessing the outcomes of such transformations (Akamani 2016) represent potential barriers that will need to be overcome in many places where an ecosystem-based adaptive governance of agroforestry is being considered. Perhaps the biggest hurdle is gaining the support of policy-makers and other stakeholders on the need for such a transition (Walters 2007). Nonetheless, success storeys such as the FMNR in Niger and the CAC program in Cuba provide hopeful and important insights into the navigation of change toward ecosystem-based adaptive governance of agroforestry systems for more inclusive, holistic, and bottom-up approaches to agroforestry development.

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